PB81-199374

Evaluation of the Effectiveness of Granular Activated Carbon Adsorption and Aquaculture for Removing Toxic Compounds from Treated Petroleum Refinery Effluents

Oklahoma State Univ.
Stillwater

Prepared for

Robert S. Kerr Environmental Research Lab.
Ada, OK

Apr 80

U.S. Department of Commerce
National Technical Information Service
NTIS.

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/2-81-067	2. ORD Report
3. RECIPIENT'S ACCESSION NO. PB81 199374	
4. TITLE AND SUBTITLE Evaluation of the Effectiveness of Granular Activated Carbon Adsorption and Aquaculture for Removing Toxic Compounds from Treated Petroleum Refinery Effluents	5. REPORT DATE April 1980 (preparation date)
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Sterling L. Burks	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Water Quality Research Laboratory, Oklahoma State University, Stillwater, OK 74074	10. PROGRAM ELEMENT NO. CBGB1C
	11. CONTRACT/GRANT NO. Grant No. R-805307-01
12. SPONSORING AGENCY NAME AND ADDRESS U.S. Environmental Protection Agency, Robert S. Kerr Environmental Research Laboratory, P. O. Box 1198, Ada, Oklahoma 74820	13. TYPE OF REPORT AND PERIOD COVERED Final/8-77 to 7-79
	14. SPONSORING AGENCY CODE 600/15
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

Activated carbon adsorption isotherms of prepared aqueous solutions of toluene, 2,4-dimethyl phenol, naphthalene, benzo(a)pyrene, chrysene, pyrene, acenaphthene, phenanthrene, fluoranthene, and fluorene on activated carbon were determined by laboratory studies to estimate the optimum loading capacity under ideal conditions. The adsorption capacity and loading capacity of the pulverized activated carbon for the specific organic compounds was calculated with the Freundlich equation.

Effectiveness of activated carbon for removal of organic compounds from a petroleum refinery wastewater was evaluated with a pilot-scale treatment system on-site at a refinery. Comparison of effluent quality from the activated carbon versus conventional biological treatment and aquaculture in aerated lagoons as measured by chemical criteria and continuous flow bioassays with fathead minnows and benthic macroinvertebrates showed the activated carbon to be effective in removing organic compounds and reducing toxicity of the wastewater.

A literature review of activated carbon treatment indicated considerable variation in estimates for both capital investments and annual operating costs.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Petroleum refining Waste treatment Activated carbon treatment Aquaculture Toxicity	Pilot-scale treatment systems Isotherms Economics Bioassay Biological Indices	68D

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED	21. NO. OF PAGES
	20. SECURITY CLASS *(This page)* UNCLASSIFIED	22.

EPA Form 2220-1 (9-73)

72

EPA 600/2-81-067
April 1981

PB81-199374

EVALUATION OF THE EFFECTIVENESS OF GRANULAR ACTIVATED CARBON ADSORPTION AND AQUACULTURE FOR REMOVING TOXIC COMPOUNDS FROM TREATED PETROLEUM REFINERY EFFLUENTS

by

Sterling L. Burks
Water Quality Research Laboratory
Oklahoma State University
Stillwater, Oklahoma 74074

EPA Grant No. R-805307-01

Project Officer

John E. Matthews
Source Management Branch
Robert S. Kerr Environmental Research Laboratory
Ada, Oklahoma 74820

PRODUCT OF:
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

ROBERT S. KERR ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
ADA, OKLAHOMA 74820

DISCLAIMER

This report has been reviewed by the Robert S. Kerr Environmental Research Laboratory, U.S. Environmental Protection Agency, and approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the U.S. Environmental Protection Agency, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques and new technologies through which optimum use of the nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate and management of pollutants in groundwater; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries, and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report evaluates the effectiveness of two advanced wastewater treatment schemes in removing selected priority pollutants from petroleum refinery wastewaters. The effectiveness of activated carbon for removal of selected priority pollutants from petroleum refinery wastewaters was evaluated under laboratory conditions. In addition, pilot-scale aquaculture and dual media-activated carbon treatment systems were evaluated onsite for their effectiveness in removing priority pollutants that have been found in refinery wastewaters.

Clinton W. Hall
Director
Robert S. Kerr Environmental Research Laboratory

ABSTRACT

The effectiveness of activated carbon for removal of selected priority pollutants from petroleum refinery wastewaters was evaluated under both laboratory and field conditions. The effectiveness of aquaculture was evaluated under field conditions.

Activated carbon adsorption isotherms of prepared aqueous solutions of toluene, 2,4-dimethylphenol, naphthalene, benzo(a)pyrene, chrysene, pyrene, acenaphthene, phenanthrene, fluoranthene, and fluorene were determined by laboratory studies to estimate the optimum loading capacity under ideal conditions. The adsorption capacity and loading capacity of the pulverized activated carbon for the specific organic compounds was calculated with the Freundlich equation.

Effectiveness of activated carbon and aquaculture for removal of organic compounds from a treated petroleum refinery wastewater was evaluated with a pilot-scale treatment system on-site at a refinery. Comparison of effluent quality from the two pilot systems versus conventional biological treatment in aerated lagoons was measured by chemical criteria and continuous-flow bioassays with fathead minnows and benthic macroinvertebrates. The activated carbon and aquaculture pilot systems were shown to be effective in removing organic compounds and reducing toxicity of the treated wastewater.

A literature review of activated carbon treatment revealed considerable variation in estimates for both capital investments and annual operating costs. Capital investment costs for granular activated carbon facilities ranged from $540,000 - $2,300,000 (1970) to $587,000 - $3,175,000 (1978) for plants from 1 to 20 million gallons per day. Annual operating costs for granular activated carbon systems varied from 4.8¢ to 40¢ per 1,000 gallons of water treated depending upon type of wastewater and amount of pretreatment.

This report was submitted in fulfillment of Grant No. R-805307 by Oklahoma State University under sponsorship of the U.S. Environmental Protection Agency. This report covers a period from August, 1977, to July, 1979, and work was completed as of January, 1980.

TYPING GUIDE SHEET
BEGIN FIRST LINE OF TEXT HERE
CENTER OF PAGE
TOP OF IMAGE AREA
DROPPED HEAD; BEGIN SECTIONS HERE

CONTENTS

Foreword iii
Abstract iv
Figures. vi
Tables vii
Acknowledgements xi

1. Introduction 1
Literature review: effectiveness of activated carbon for treatment of petroleum refinery wastewater. 1
Laboratory determination of carbon adsorption isotherms . 4
On-site evaluation of pilot scale aquaculture and dual-media activated carbon treatment systems. 6
2. Materials and Methods. 8
Determination of carbon adsorption isotherms for selected priority pollutants. 8
On-site evaluations of pilot scale dual-media activated carbon and aquaculture treatment systems for removal of toxic contaminants from petroleum refinery wastewater 10
3. Results and discussion 14
Laboratory determination of carbon adsorption isotherms . 14
On-site evaluations of pilot scale dual media-activated carbon treatment systems for removal of toxic contaminants from petroleum refinery wastewater. 15

References 22
Appendices
A. Carbon adsorption isotherm data. 25
B. Chemical data from on-site evaluation of dual media-activated carbon and aquaculture treatment systems for removal of toxic constituents from petroleum refinery wastewater. 46
C. Species list of benthic macroinvertebrates from on-site evaluation of dual media-activated carbon and aquaculture treatment systems for removal of toxic constituents from petroleum refinery wastewater. 52

BEGIN LAST LINE OF TEXT
BOTTOM OF IMAGE AREA, OUTSIDE DIMENSION FOR TABLES AND ILLUSTRATIONS
3.8"

PAGE NUMBER
EPA-287 (Cin.)
(4-76)

FIGURES

Number		Page
1	Carbon adsorption isotherm for naphthalene	26
2	Carbon adsorption isotherm for acenaphthalene	28
3	Carbon adsorption isotherm for phenanthrene	30
4	Carbon adsorption isotherm for fluoranthene	32
5	Carbon adsorption isotherm for fluorene	34
6	Carbon adsorption isotherm for pyrene	36
7	Carbon adsorption isotherm for chrysene	38
8	Carbon adsorption isotherm for 2,4-dimethylphenol	40
9	Carbon adsorption isotherm for toluene	42
10	Carbon adsorption isotherm for benzo(a)pyrene	44
11	Quantity of benzo(a)pyrene remaining in solution at increasing levels of activated carbon	45

TABLES

Number		Page
1	Excitation and Emission Frequencies Used for Fluorescent Analysis and Percent Recoveries from Initial Concentrations (C_o)	9
2	Summary of Freundlich Parameters	14
3	Percent Mortality of Fathead Minnows (Pimephales promelas) After 32 Days Continuous Exposure to Normal Aerated Lagoon, Pilot-scale Aquaculture and Pilot-scale Dual Media-Activated Carbon Treated Oil Refinery Wastewater	16
4	Response of Benthic Macroinvertebrate Organisms to Selectively Treated Oil Refinery Wastewater.	16
5	Index of Similarity of Assemblages of Benthic Macro-invertebrate Organisms Exposed to Oil Refinery Effluents	17
6	Concentration of BOD in Conventional Aerated Lagoon, Pilot-scale Aquaculture, and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	17
7	Concentration of COD in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	18
8	Concentration of TOC in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	18
9	Concentration of Nitrate Nitrogen in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater	19
10	Concentration of Nitrite Nitrogen in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater	19
11	Concentration of Total Phosphate in Conventional Aerated Lagoon, Pilot-scale Aquaculture and dual Media-Activated Carbon Treated Petroleum Refinery Wastewater	20

Number		Page
12	Concentration of Dissolved Phosphate in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	20
13	Concentration of Ammonia Nitrogen in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	20
	Appendix A	
A-1	Carbon Adsorption Isotherm Data for Naphthalene	25
A-2	Adsorption Capacity of Carbon for Naphthalene	25
A-3	Carbon Adsorption Isotherm Data for Acenaphthene.	27
A-4	Adsorption Capacity for Acenaphthene.	27
A-5	Carbon Adsorption Isotherm Data for Phenanthrene.	29
A-6	Adsoption Capacity of Carbon for Phenanthrene	29
A-7	Carbon Adsorption Isotherm Data for Fluoranthene.	31
A-8	Adsorption Capacity of Carbon for Fluoranthene.	31
A-9	Carbon Adsorption Isotherm Data for Fluorene.	33
A-10	Adsorption Capacity of Carbon for Fluorene.	33
A-11	Carbon Adsorption Isotherm Data for Pyrene.	35
A-12	Adsorption Capacity of Carbon for Pyrene.	35
A-13	Carbon Adsorption Isotherm Data for Chrysene.	37
A-14	Adsorption Capacity of Carbon for Chrysene.	37
A-15	Carbon Adsorption Isotherm Data for 2,4-Dimethyl Phenol	39
A-16	Adsorption Capacity of Carbon for 2,4-Dimethyl Phenol	39
A-17	Carbon Adsorption Isotherm Data for Toluene	41
A-18	Adsorption Capacity of Carbon for Toluene	41
A-19	Carbon Adsorption Isotherm Data for Benzo(a)pyrene.	43
	Appendix B	
B-1	Concentration of Total Dissolved Solids in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	46

Number		Page
8-2	Concentration of Suspended Solids in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater	46
8-3	Concentration of Turbidity in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	47
8-4	Concentration of Chloride in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	47
8-5	Concentration of Sodium in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	47
8-6	Concentration of Calcium in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	48
8-7	Concentration of Magnesium in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	48
8-8	Concentration of Potassium in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	48
8-9	Concentration of Iron in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	49
8-10	Concentration of Lead in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	49
8-11	Concentration of Zinc in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	49
8-12	Concentration of Copper in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	50

Number		Page
B-13	Concentration of Chromium in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	50
B-14	Concentration of Cadmium in Conventional Aerated Lagoon, Pilot-scale Aquaculture and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	50
B-15	Concentration of Manganese in Conventional Aerated Lagoon, Pilot-scale Aquaculture, and Dual Media-Activated Carbon Treated Petroleum Refinery Wastewater.	51
	Appendix C	
C-1	Species Composition of Benthic Macroinvertebrates Exposed to Normal Lagoon Treated Oil Refinery Wastewater	52
C-2	Species Composition of Benthic Macroinvertebrates to Aquaculture Treated Oil Refinery Wastewater.	55
C-3	Species Composition of Benthic Macroinvertebrates Exposed to Dual Media-Activated Carbon Treated Effluent.	58

ACKNOWLEDGEMENTS

This study was conducted by the Oklahoma State University Water Quality Research Laboratory. Grateful acknowledgement is expressed for the hard work by the entire staff; Conrad Kleinholz, Sarah Schatz, Elaine Stebler, Randy Staggs, Geof Russell, Barbara Mays, Terry King, Kelly Lawrence and Karen Bredel. Without their assistance this project would not have been possible.

The cooperation and assistance of the Oil Refiners Waste Control Council in performance of the on-site tests were critical to the success of this project. Many different individuals from the refineries offered valuable advise and assisted in operation of the on-site facility. We sincerely appreciate and acknowledge their contributions.

We especially express our gratitude to the EPA project officer, John Matthews, for valuable guidance during the project and for editorial assistance in preparation of the final report. In addition, we are grateful for technical assistance provided by Leon Myers, and his staff at EPA, Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma.

SECTION 1

INTRODUCTION

LITERATURE REVIEW: EFFECTIVENESS OF ACTIVATED CARBON FOR TREATMENT OF PETROLEUM REFINERY WASTEWATER

Activated carbon is well known as a good adsorbent for removal of organic chemical compounds from aqueous solutions (Hassler 1963). The mechanism of adsorption is generally thought to involve attraction of nonpolar organic molecules for carbon helixes on the activated carbon surface and in internal pores via Van der Waal forces (Puri 1970). Activated carbon has a high surface area to volume ratio which is indicative of the porous structure. Polar organic molecules are attracted to surface oxides, i.e., carbonyl groups on the activated carbon surface, possibly through hydrogen bonding. In general, commercial activated carbon adsorbs greater quantities of nonpolar organic chemical compounds, such as, aliphatic and aromatic hydrocarbons, than polar compounds, such as, carbohydrates and amino acids. The organic chemicals which are relatively insoluble in water (hydrophobic) are more readily adsorbed onto activated carbon.

These properties have led to the application of activated carbon for treatment of wastewaters containing high concentrations of organic chemicals. Laboratory batch studies have shown activated carbon to be effective in removing total organic carbon (TOC) from a variety of industrial wastewaters (Hager, D.G., 1974).

Primary objectives of activated carbon systems in the petroleum refining industry are reductions of TOC and Chemical Oxygen Demand (COD) in final effluents by adsorption of biorefractory organic compounds. However, some classes of organic compounds which exert COD are not adsorbed by activated carbon (Shell et al. 1971) and weakly adsorbed compounds may be desorbed before adsorptive capacity of the carbon is attained (Grieves et al. 1978). Adsorptive capacity of activated carbon is related to surface area, pore size, and source (bone, coal, wood) (DeJohn 1974; DeJohn and Adams 1975). Activated carbon loses some adsorptive capacity when regenerated, presumably due to plugging of pores. Adsorptive capacity of carbon is inversely related to initial concentrations of organic compounds. Use of activated carbon in petroleum refinery effluents requires prefiltration of oils and colloidal organics to reduce carbon fouling (Paulson 1970).

Activated carbon is available in granular or powdered form. Granular carbon is used in fixed-or-expanded-bed columns which are usually upflow pressure systems. Granular carbon may be used to treat wastewaters which have received primary treatment, but a full-scale granular carbon plant could

Preceding page blank

achieve only 50% of the removal capacity predicted from pilot-scale studies (Engineering Science 1975). Therefore, it may not be economically feasible to use granular carbon for treatment of effluents from primary treatment facilities. Another full-scale project used granular activated carbon to successfully treat combined storm water and process wastewaters (Loop 1975).

Adsorptive capacities of activated carbons vary with type and brand, as well as between granular and powdered. Activated carbon made from lignite coal has larger pores than that made from bituminous coal, and has a higher adsorptive capacity when virgin carbons of the two types are compared. COD loadings of lignite carbon were 0.21 and 0.65 lb COD/lb of carbon, as compared to bituminous capacity of 0.16 and 0.46 lb COD/lb carbon when both were tested on two refinery effluents (Paulson 1975). However, these differences in adsorptive capacity disappeared after several carbon regeneration cycles. Estimated capacities for granular carbons range from 0.5-0.6 lb COD/lb carbon (Engineering Science 1975) for the petroleum industry to 0.2-0.4 lb COD/lb carbon for the petroleum refinery wastewaters. Loop (1975) loaded granular carbon with combined storm and process wastewaters in a full-scale system to 0.25 lb COD/lb carbon, and calculated the adsorptive capacity as 0.3-0.35 lb COD/lb carbon. In a pilot comparison of experimental and commercially available carbons, calculated capacities of commercial granular carbon were 0.14 g TOC and 0.41 g COD/g carbon while experimental high surface area granular carbon was calculated to have capacities of 0.19 g TOC and 0.63 COD/g carbon (Grieves et al. 1978). The same study compared powdered carbons and reported apparent organic loadings of 0.6-0.9 g COD/g commercial carbon and 0.75-1.25 g COD/g high surface area carbon. The apparent loading was defined as the incremental removal of organics beyond a control divided by the powdered carbon dose or make-up, and may have been achieved by biological regeneration of the carbon associated with the high (100 day) sludge age of the treatment system.

Most research with granular carbon is based on the addition of adsorption systems to polish the effluent of an activated sludge system or its equivalent, following filtration of the effluent. In the absence of a biological treatment system, granular carbon contactors can be installed after deoiling, roughing biological treatment (trickling filter or rotating biological contactor), and mixed-media filtration treatment systems. The stated advantage of this option is smaller required land area, but the contactor must be 1.5 to 2 times that for polishing biologically treated effluents (Engineering Science 1975). Both of these options require prechlorination to prevent biological growth and fouling in the columns. Sulfide production in carbon columns has also been noted (McCrodden 1975). Adsorptive capacity for treatment of bio-effluents is generally less than that attained in treatment of process wastewaters. Estimated removal of COD by granular activated carbon is 32-79%, depending on carbon used and wastewater quality (Engineering Science 1975). Full-scale treatment of combined storm and process wastewaters with granular activated carbon removed 80% of total COD (Loop 1975). Pilot-scale treatment of activated sludge unit effluent with commercial granular carbon produced 87% reduction of soluble organic carbon (SOC) and 86% removal of soluble COD (SCOD) in comparison with Amoco experimental high surface area granular carbon, which removed 83% SOC and 86% SCOD (Grieves et al. 1978). The capability of Amoco

experimental high surface area powdered activated carbon to enhance removal of organic compounds was evaluated in a large pilot-scale activated sludge treatment system. The overall removal was 88% SOC and 79% SCOD. However, a earlier evaluation of a full-scale powdered carbon-activated sludge system could achieve only 20-36% COD (total) removal, with concurrent reductions of suspended solids and total Biochemical Oxygen Demand (BOD) of 49-56% and 2-76%, respectively (Rizzo 1976).

Use of powdered activated carbon (PAC) to treat wastewaters was pioneered and patented by DuPont. The carbon is added as a water slurry to activated sludge aeration basins. Enhancement of the sludge system process includes color removal, better flocculation and sludge settling (Rizzo 1976), and elimination of foaming in the sludge clarifier (Rizzo 1976, Grieves et al. 1978). PAC also negates or minimizes shocks of toxic substances to a sludge system (Adams 1974, Rizzo 1976).

Use of powdered carbon may be minimized by sludge recycling to maximize sludge age up to 100 days while retaining hydraulic retention times of approximately 12 hours (Grieves et al. 1977, 1978). A cost advantage of this system is the low quantities of carbon used, which permits wasting of the spent carbon rather than regeneration, an option not available with granular carbon systems. Use of powdered carbon also eliminates the necessity of construction of contactors used with granulated carbon.

Estimation of treatment costs is difficult since each system reacts differently. Pilot studies must be conducted to obtain design data from which cost estimates can be derived. Comparison of design criteria is also difficult since systems may have different design parameters, such as TOC, COD, or suspended solids reductions. Capital cost estimates for granular activated carbon systems range from $540,000 to $2,300,000 for plants from 1-10 million gallons per day (mgd)(Paulson 1970) and $587,000-$3,175,000 for plants from 2-20 mgd designed to meet SCOD requirements of 30 mg/l (Grieves et al. 1978). The estimated capital costs for powdered activated carbon systems ranged from $406,000-$912,000 with regeneration capabilities and $123,000-$1,050,000 without regeneration for plants of 2-20 mgd capacity. These systems were designed for SCOD requirements of 45 mg/l with 50 mg/l PAC dose and 100-day sludge age (Grieves et al. 1978).

Operating cost estimates for granular carbon systems range from 4.8-10.9¢/1,000 gal for primary effluents and 5.3-9.4¢/1,000 gal for secondary effluents based on BOD removal (Paulson 1970). The costs have been estimated as high as 40¢/1,000 gal for COD removal (Engineering Science 1975). A full-scale project treated combined process and storm waters for 40-49¢/1,000 gal or 18-24¢/lb COD removed for a 2-year period (Loop 1975).

Operation of two plants using powdered carbon cost 1.5-7.0¢/1,000 gal (Adams 1974) and 1.7-4.3¢/1,000 gal (Rizzo 1976). These costs varied depending on influent flow and quality. Estimated regeneration costs were 1-10¢/lb (Adams 1974).

Costs of treatment of petroleum refinery wastewaters to meet effluent guidelines are estimated to increase from 5.2¢/barrel to 9.1¢/barrel between

1977 and 1983, and to 10.8¢/barrel by 1985 (Smith and Leone 1975). Effluent guidelines require Best Available Technology Economically Achievable (BATEA) and call for reduction of process wastewater flows by as much as 48% and additional end-of-pipe treatment to reduce effluent levels of most organic compounds to near zero (Engineering Science 1975). Implementation of these guidelines has been delayed from 1983 to 1984 by the Clean Water Act (PL 95-217). The effluent guidelines are based on use of activated carbon adsorption systems to improve effluent quality.

LABORATORY DETERMINATION OF CARBON ADSORPTION ISOTHERMS

Adsorption isotherms were determined for specific organic compounds identified in the 1976-1977 EPA survey of petroleum refinery wastewaters; toluene, 2,4-dimethylphenol, naphthalene, benzo(a)pyrene, chrysene, pyrene, acenaphthene, phenanthrene, fluoranthene, and fluorene.

ASTM's standard practices for adsorptive capacity of carbon by isotherm techniques recommends analysis of the filtrates by the appropriate method for the constituent of interest. The method of TOC analysis for toluene and 2,4-dimethylphenol was selected since this method was rapid and not as susceptible to experimental error as extraction-quantification procedures. For the remainder of the compounds this method was not sensitive enough to detect the low quantities involved due to the lower solubilities of the polynuclear aromatic hydrocarbons (PAH's).

Initially, it was anticipated that quantities of these compounds could be determined by solvent extraction with methylene chloride, evaporation of excess solvent, and quantification by gas chromatography according to EPA (1977) procedure for base neutrals. However, considerable difficulties were encountered with loss of naphthalene during all steps in the procedure. Recoveries from prepared stock solutions were extremely low, i.e., 20-30% during the initial experiments. A 50% loss was encountered just during the concentration stage. After procedural modifications, recoveries were still only 40% of quantities added. Acheson et al. (1976) pointed out several factors which affected the extraction and analysis of PAH's in water. Possible explanations given were adsorption onto suspended solids, adsorption of PAH's onto the glass or degradation within the vessel. Variations in extraction efficiencies of PAH's from pure water solutions appeared to be related to initial concentration. At relatively high concentrations (0.3 mg/l) 80% recoveries were obtained, but at lower concentrations (0.02 mg/l) recoveries dropped to 40%.

Ultraviolet and fluorescence spectrophotometry have been successfully used for the determination of PAH's in environmental samples. While ultraviolet spectrophotometry is used extensively in air pollution analysis, it is not sensitive enough for most applications in water analysis. Fluorescence spectrophotometry is far more sensitive and Sawicki (1970 a&b) reported detection limits of PAH's of between 3 and 200 ng depending upon the particular compound. Kunte (1967) described in detail a method for the simultaneous detection of 10 PAH's from water, dust, soil, and plant extracts. This method involved fluorimetric analysis of PAH's extracted from Thin Layer

Chromatography (TLC) plates after resolution. Quantities of 1 ng were detected. Borneff and Kunte (1976 and 1969) and Reichert et al. (1971) also used this procedure for determination of PAH's in aqueous samples. Thomas et al. (1960) stated that the fluorescence of a compound was often found to be enhanced on paper and that "this is consistent with the theory which states that any factor hindering vibrational modes may favor fluorescence by minimizing the degradation of electronic energy." Sawicki et al. (1960) considered pentane as the ideal solvent for mixtures containing PAH's and reported activation and fluorescence spectra for a large number of these compounds. Fluorescence and excitation peak maxima of 35 aromatic compounds in cyclohexane were reported by McKay and Latham (1972). Borneff and Fisher (1963, Borneff and Kunte (1969), and Pyriki (1959) used benzene in their fluorescence studies of PAH's.

Since most studies of the fluorescence and adsorption spectra of aromatic molecules have been made with solutions, the emitting or absorbing molecule may be influenced by the surrounding solvent molecules which can cause significant changes in its photophysical properties. The observed spectral and photophysical parameters are characteristic of the molecule in its solvent environment rather than of its isolated molecules (Birks 1970).

Nakajima (1976) studied the spectral behaviors of several aromatic hydrocarbons with particular regard to the effects of water as a solvent and the dissolved states of the hydrocarbons. Nakajima found that the molecular fluorescence spectra of small condensed aromatic hydrocarbons which are fairly soluble in water could be observed in aqueous solutions, while only the emission spectra for aggregates or microcrystals appear with somewhat larger hydrocarbons. The larger hydrocarbons formed complex molecular aggregates depending on various conditions of preparation which made them unsuitable for obtaining homogeneous aqueous solutions. However, the concentrations Nakajima used seem to be an order of magnitude too high for "true" aqueous solutions.

The photophysics of aromatic molecules is a complex subject in itself, and this study was not intended to investigate the fluorescent properties of these compounds but merely to use fluorometry as a quantitative tool. One difficulty often encountered in the measurement of the room-temperature fluorescence of aromatic hydrocarbons is quenching of luminescence. The fluorescence intensity of very dilute solutions of a fluorescent substance is proportional to the concentration of the substance. In more concentrated solutions, the fluorescence intensity increases at a slower rate than the concentration, i.e., the ratio of the radiated to the absorbed quanta begin to decrease. Such a decrease in fluorescence yield is known as quenching.

Fluorescence quenching can be caused by other factors such as small concentrations of impurities or the presence of other PAH's in solution. Since the solutions were of one pure compound, care was taken to avoid concentration quenching. Standard curves were prepared for the compounds both for quantitative purposes and for determining an appropriate working range of concentrations to minimize quenching.

ON-SITE EVALUATION OF PILOT-SCALE AQUACULTURE AND DUAL-MEDIA ACTIVATED CARBON TREATMENT SYSTEMS

The national goal of the 1972 amendments to the Federal Water Pollution Control Act was designed to achieve zero-pollutant discharge by 1985. A pollutant was defined as any substance which directly or indirectly, through the food chain, caused a deleterious effect upon any organism in the aquatic environment. The Environmental Protection Agency's National Pollutant Discharge Elimination System (NPDES) was designed to implement Congress' intent of removing all toxic substances from all point sources of wastewater discharge. The interim goal was to achieve fishable-swimmable water quality in all surface waters by 1983. EPA elected to control water pollution through application of chemical water quality standards for all point source discharges, since it was not practical at the time to measure the toxicity or deleterious effects of wastewaters upon any organism within the aquatic environment. However, the ultimate standard or measure of wastewater quality would have to be a measure of its potentially direct or indirect deleterious effects upon any organism in the aquatic environment. Therefore, measurement of the toxic effects of wastewaters upon aquatic organisms may be less complicated in the long run than quantifying the hundreds of known toxic compounds which could occur in wastewater. Many toxic components are difficult to analyze quantitatively due to the trace levels of concentration in wastewaters and lack of suitable analytical techniques with necessary sensitivity. The response of aquatic organisms to the chemical contaminants in a wastewater environment acts as an integrating effect to summate all of the deleterious effects of all of the components in the wastewater. Therefore, it is imperative that effective, acceptable toxicity tests be developed to determine the potential deleterious effects of any wastewater discharge.

Evaluation of deleterious effects of wastewaters to aquatic organisms is usually accomplished by exposing the organisms to the wastewater for a selected time interval and measuring responses of the organisms, such as percent mortality. These types of tests are very useful for interpreting the effects of a wastewater upon a single species; however, it is often not possible to perform such tests on many different species of aquatic organisms. Many species of aquatic organisms are not easily cultured or maintained under laboratory conditions and, therefore, it is extremely difficult to perform acute toxicity tests with certain types of organisms. In additiona, the selected time of exposure may not be of sufficient duration to produce lethal effects in the organisms. Aquatic organisms are often more susceptible to toxic substances at critical stages in the life cycle, i.e., during the larval stages. Therefore, it is difficult to assess the total potential of deleterious effect unless exposures are conducted for an entire life cycle of the organism. Life cycle studies may not be feasible on long-lived species because of limitations of time and facilities. An alternative benthic macroinvertebrate bioassay test has been developed which appears to offer several advantages over single-species bioassays (Burks and Wilhm 1977).

Briefly, the test utilizes as test organisms benthic macroinvertebrate organisms colonized on artificial substrate samplers in unpolluted waters. The well-balanced macroinvertebrate communities are exposed to the test

effluents or chemical substances for a period of 32 days. Changes in diversity, number of taxa, and density of individuals during the exposure period are used as comparative measures of deleterious effects upon the aquatic organisms. The major advantages of the benthic macroinvertebrate bioassay test are the exposure of multiple species of aquatic organisms at different stages in the life cycle of the species, plus the multiple effect of a combined assemblage of organisms being exposed to the test effluent. The major objective in this phase of the project was to evaluate the effectiveness of a pilot-scale dual-media filtration-activated carbon adsorption system and a pilot-scale aquaculture wastewater treatment system for removing toxic substances from a normal lagoon treated petroleum refinery wastewater.

SECTION 2

MATERIALS AND METHODS

DETERMINATION OF CARBON ADSORPTION ISOTHERMS FOR SELECTED PRIORITY POLLUTANTS

Calgon Filtrasorb 300 (Calgon Corp., Pittsburgh, PA) was selected for performing the adsorption isotherm tests after a preliminary evaluation of two other types. Calgon Filtrasorb 300 showed highest adsorptive capacity for removal of toluene from aqueous solutions. The commercial granular carbon was pulverized with a mortar and pestle until it would pass through a number 325 mesh sieve. The pulverized-sieved carbon was oven-dried overnight at 105°C prior to use. Carbon quantities for each sample were either weighed directly to the nearest 1×10^{-4} g on an analytical balance or a carbon-water slurry was used. The carbon slurry, containing 1 mg carbon per 1 ml slurry, was prepared by adding 1.0000 g carbon to 1.0 liter of deionized-distilled water. A range of five or six carbon dosages was chosen for each compound appropriate to the concentration of the compound. Triplicate samples were done for each weight of carbon.

Aqueous solutions of the specific chemical compounds were prepared by addition of a weighed quantity of the chemical to a large flask containing a volumetric measure of deionized-distilled water. The solution was mixed on a magnetic stirrer for one hour and individual sample volumes were taken from this solution. For those compounds which were not water soluble, an ethanol stock solution was prepared. Small volumes of this stock solution were added to the water to give the desired concentration (Dobbs et al. 1978).

The sample was immediately filtered by gravity through a Whatman 42 glass fiber filter pad or by pressure filtration through a Gelman Type A-E glass fiber filter pad. The entire procedure for pyrene, benzo(a)pyrene, acenaphthene, and chrysene was performed in a dark room. All adsorption isotherms were determined at pH 5.0 and conducted at ambient room temperature which ranged from 20 to 24 degrees C.

The quantity of 2,4-dimethylphenol and toluene remaining in aqueous solutions after contact with the carbon was analyzed with a Beckman (TOC) instrument. The concentration of naphthalene, benzo(a)pyrene, chrysene, pyrene, acenaphthene, phenanthrene, fluoranthene, and fluorene was determined using an Aminco-Bowman Fluorescent Spectrophotometer. The excitation/emission spectrum of the sample was obtained by manually incrementing across the excitation wavelength while scanning the emission wavelengths to determine the optimum frequencies. Checks were then made to determine the slit width for best resolution and sensitivity. Wavelengths used for quantification

were set at the most intense activating frequency and the most intense fluorescence wavelength for the particular compound (Table 1). The following settings were used on the spectrophotofluorometer: sensitivity = 50, slit arrangement = 3 (except for naphthalene, which was 5), and the phototube was type IP21.

TABLE 1. EXCITATION AND EMISSION FREQUENCIES USED FOR FLUORESCENT ANALYSIS AND PERCENT RECOVERIES FROM INITIAL CONCENTRATION (C_o)

Compound	A	B	%
naphthalene	280	330	97
acenaphthalene	291	336	97
fluorene	270	310	96
pyrene	336	379	92
phenanthrene	254	364	101
chrysene	319	403	97
fluoranthene	285	463	87
benzo(a)pyrene	392	506	79
2,4-dimethylphenol	*	*	92
toluene	*	*	88

A = excitation frequency in nm
B = emission frequency in nm
% = percent recovery of initial concentration
* not applicable, analyzed by TOC

The linearity curve method was used for quantification. The concentration of prepared aqueous solutions of the compound to be analyzed was graphed against the fluorescent intensity. The data were analyzed by linear regression equation. The correlation coefficient (r) for all the standard curves was greater than 0.997.

The isotherm data were analyzed by the Freundlich equation;

$$\frac{X}{M} = KC_f^{1/n}$$

The logarithmic form of the above equation was used for calculating the correlation coefficient (r) to determine "goodness of fit" of the data and to derive the Freundlich parameters;

$$\log \frac{X}{M} = \log K + 1/n \log C_f$$

Where:

C_o = initial quantity of solute in mg

C_f = final quantity of solute in mg

$X = C_o C_f$ = quantity of solute absorbed in mg

M = weight of carbon in g

K = intercept at $C_f = 1$ ($\log C_f = 0$)

1/n = slope of the line.

ON-SITE EVALUATIONS OF PILOT-SCALE DUAL MEDIA-ACTIVATED CARBON AND AQUACULTURE TREATMENT SYSTEMS FOR REMOVAL OF TOXIC CONTAMINANTS FROM PETROLEUM REFINERY WASTEWATER

A pilot-scale dual media-activated carbon (DM-AC) treatment system mounted in a mobile trailer was moved on-site to an oil refinery for this evaluation. The dual-media filter column consisted of 20.3 cm diameter polyethylene pipe, 1.27 cm thick walls, and length of 168 cm (Ryerson Co., Dallas, Texas). The column was filled sequentially with pea-sized gravel (10 cm), #1220 garnet sand (35 cm), and #2 anthracite coal (Chase & Assoc., Tulsa, Okla.). The filtration column was designed for downflow gravity filtration with valving for hydraulic backflushing.

Activated carbon columns were constructed from the same size polyethylene pipe used for the dual-media filter columns. Plumbing connections were designed for sequential flow through the series of four activated carbon columns. Each column was filled with approximately 13.5 kg (height of carbon was 152 cm in column) of carbon. Carbon was changed prior to exceeding a loading capacity of 1 g of COD per 10 g of carbon. Two types of granular carbon were used in the evaluation; Darco (ICI United States, Wilmington, DE) and Filtersorb 400 (Calgon Corp., Pittsburgh, PA).

A pilot-scale aquaculture treatment system (sponsored as a demonstration project by the Oil Refiners' Waste Control Council) was constructed on-site at the refinery. The major components of the aquaculture system consisted of a sequential series of six vinyl-lined round pools, 5.48 m diameter by 1.2 m deep. The first three pools in the series were operated for optimum growth of planktonic algae. The fourth pond in the series was stocked with 2,898 kg/ha of mussels and 951 kg/ha of Tilapia aurea. The fifth pond in the series was stocked with 7,730 kg/ha of mussels and 2,183 kg/ha of Tilapia. The sixth pond was stocked with 2,319 kg/ha of mussels, 2,533 kg/ha of Tilapia, and 0.93 m^2 of the emergent plant Primrose Willow (Jussiaea diffusa). Flow rate of the wastewater through the aquaculture system was maintained at 3 to 4 liters per minute for an estimated retention time of 3.7 to 5 days per pond.

Influent water to both the pilot-scale aquaculture and the DM-AC treatment systems was pumped from the point of final discharge from the oil refinery

wastewater treatment system. The oil refinery wastewater treatment system consisted of sequential treatment with a primary API oil-water separator, a dissolved air flotation system, an aerated lagoon, and waste stabilization lagoons. Water from each of the test units passed continuously through duplicate artificial streams (1.2 l/min). The flow rate was designed to deliver a volume equivalent to the total volume of the artificial streams in 3.5 hours. The recommended flow rate for continuous-flow bioassays is a volume equivalent to that of the test container in 6 to 8 hours (EPA 1975).

A chemical ion probe monitoring chamber measured pH, temperature, dissolved oxygen, and conductivity (Hydrolab Corp., Austin, Texas). Each test stream was switched via an industrial timer-controlled 3-way solenoid valve to flow through the chemical ion probe chamber for 15 minutes per hour. The data from the ion probe monitoring meter were recorded every 5 minutes on a 6.3 mm (6.25 in) magnetic tape data logger (Metrodata Corp., Norman, Okla.). The day, hour, minutes, seconds, and an identification code for each stream were also logged at the same time as the ion probe data.

TOC analyses of the refinery wastewater samples were performed on a Beckman 915 TOC Analyzer. COD was analyzed by the dichromate-sulfuric acid standard method (APHA 1976). Alkalinity, hardness, suspended solids, and inorganic ammonia were analyzed with APHA standard methods. Wastewater samples for heavy metal analyses were collected in polyethylene bottles and transported to the laboratory within 24 hours. The samples were filtered through Gelman 0.45 micron membrane filters. The filtrate was acidified to pH 2.0 with concentrated nitric acid and analyzed as dissolved metals. The membrane filter and filtered materials were reflux digested in concentrated nitric acid two times and dissolved in 3 ml of hot 50% hydrochloric acid. The sample was diluted to desired volume with 0.2 N nitric acid. This fraction was reported as suspended metals (EPA 1974).

Heavy metal analyses were performed with a Varian Techtron AA-5 Atomic Absorption spectrophotometer. Trace concentrations of cadmium, chromium, and lead were analyzed with a heated graphite analyzer (Perkin Elmer) attachment for the atomic absorption instrument. Quality control was maintained with EPA-recommended procedures and reference standards. Corrections for matrix interferences in cadmium, chromium, and lead analyses were made by method of standard additions. Organic background was corrected for by subtracting adsorbance obtained with a hydrogen continuum lamp.

The artificial streams were constructed of redwood with a fiberglass interior. A paddlewheel was installed to create currents in the artificial streams since the flow rate of test effluents was not sufficient to cause adequate currents. The current velocity was estimated to be from 2.0 to 4.0 cm/second (2.5 to 7.8 ft/minute). The fathead minnows were placed in the artificial streams in cages constructed from 0.25 in mesh polyethylene netting. Ten fish were placed in each artificial stream. All fathead minnows used in the bioassay tests were laboratory raised fish from the OSU Water Quality Research Laboratory. Most of the fish were at least 90 days of age or older since an attempt was being made to obtain a spawn during the exposure.

Organisms for the benthic macroinvertebrate bioassays were obtained from a small stream approximately 20 miles east of Stillwater, Oklahoma. Multiplate artificial substrate samplers were placed in the streams for a period of six weeks to permit colonies of organisms to attach. The artificial substrate procedure has been widely used for comparing community structure in receiving waters above and below a point-source discharge (Hester and Dendy 1962, Weber 1973). The multiplate samplers are commonly designated as Hester-Dendy samplers.

Hester-Dendy artificial substrate samplers were constructed from 76 cm (3 in) squares of masonite separated by 25 cm (1 in) squares on an eyebolt (Hester and Dendy 1962). A set of 60 samplers was placed in an unpolluted natural stream and colonized by benthic macroinvertebrates for 6 weeks (Mason et al. 1973).

Hester-Dendy samplers were colonized in a pool behind a low-water dam on a stream east of Stillwater, Oklahoma (SE/4 of Section 35-R6E-T20N). After colonization, six Hester-Dendy samplers were collected for determining initial species diversity, number of taxa, and mean density of benthic organisms. The remaining 54 samplers were transported to artificial streams located near the wastewater outfall of the petroleum refinery. Samplers were placed in 2-liter polyethylene containers and transferred within 3 hr. Nine samplers were placed in each of six artificial streams, 3.6 m (12 ft) long by 0.3 m (1 ft) wide with water 22.8 cm (9 in) deep.

Two streams each were exposed to the aerated lagoon treated, the pilot-scale aquaculture treated, and the pilot-scale DM-AC treated oil refinery wastewater.

Three Hester-Dendy samplers were collected from each stream after 8, 16, and 32 days of exposure. Organisms were washed from the samplers and those retained by a 30-mesh sieve were preserved in 10% formalin within 24 hours after collection. The organisms were subsequently sorted from the debris and identified to the lowest taxa possible.

A pooled species diversity value ($\bar{d}$) was calculated for the organisms identified on the three samplers collected from each treatment stream by the following formula (Margalef 1956):

$$\bar{d} = \sum_{i=1}^{s} (n_i/n) \log_2 (n_i/n)$$

where;

n_i = number of individuals in the ith taxon

n = Total number of individuals in the collection

s = total taxa.

A mean pooled $\bar{d}$ and standard deviation were calculated from the pooled $\bar{d}$ of the two replicate streams for each treatment. Total number of taxa identified from the six Hester-Dendy samplers from the two replicate treatment streams were recorded. Mean density was calculated by dividing the total number of individuals per sampler by the area (0.144 m^2).

A similarity index was also calculated in order to compare the distribution of species and individuals of benthic macroinvertebrate organisms after exposure to the test effluents (Brock 1977). The index used in this project was originally described by Whittaker (1952), and compares the similarity of different communities with the following index:

$$Psc = 100 - 0.5 \sum_{k} [a - b]$$

where a and b are the percentages that a particular species represents of the total population of samples A and B. The absolute difference in percentage composition of each species is summed for all species, k.

SECTION 3

RESULTS AND DISCUSSION

LABORATORY DETERMINATION OF CARBON ADSORPTION ISOTHERMS

Experimental data for each of the compounds tested are presented in Appendix A. Carbon dosages are shown along with the initial concentration (C_o) and residual concentrations (C_f) after treatment with carbon. These values were then used to calculate the amount of compound removed ($C_o - C_f$) and the carbon loading (X/M). The carbon loading versus residual concentration are plotted on log-log coordinates. Adsorption capacities were calculated for various equilibrium concentrations. A summary of Freundlich parameters for the 10 compounds treated is presented in Table 2.

TABLE 2. SUMMARY OF FREUNDLICH PARAMETERS

Compound	K[(a)]	1/n	r
fluorene	196	0.57	0.95
2,4-dimethylphenol	184	0.09	0.93
acenaphthene	140	0.43	0.97
phenanthrene	135	0.45	0.89
naphthalene	123	0.41	0.99
fluoranthene	88	0.38	0.82
pyrene	66	0.24	0.92
toluene	40	0.35	0.93
chrysene	6	0.50	0.82
benzo(a)pyrene	(b)	(b)	-0.55

(a) K at C_o = 1 mg/l
(b) data did not fit Freundlich Equation, as indicated by low correlation coefficient.
r = correlation coefficient.

Correlation coefficients for 9 of the 10 compounds evaluated showed a positive correlation with the Freundlich equation. The adsorption data for BAP did not fit the Freundlich equation as indicated by the low calculated correlation coefficient of -0.55. However, the adsorption data for BAP did show a high correlation with a normal arithmetic linear regression equation ($Y = mX + b$), when the dose of carbon (mg) was plotted against quantity of

BAP adsorbed (μg), r = 0.98. Apparently the sorption mechanism for BAP was sufficiently different from the other compounds that it would not fit the Freundlich equation.

With the exception of toluene, the adsorption capacity appeared to decrease with respect to an increase in complexity of the polynuclear aromatic molecule. This trend would be predicted if the mechanism for adsorption by activated carbon is dependent upon attraction to surface sites and intraparticulate pores. An increase in either number of aromatic rings or substituents on the ring would tend to inhibit diffusion into the intraparticulate pores and thus restrict adsorption to the surface sites only.

Considerable losses of toluene were encountered between preparation of the aqueous solutions and measurement of final concentrations after mixing with the activated carbon. About 39% of the initially prepared aqueous solution was lost during the mixing and filtration steps. Mixing was performed in stoppered flasks, and pressure filtration was used to minimize losses due to volatilization; however, these precautions apparently were still not adequate to prevent considerable loss of toluene. The data used in determining the Freundlich parameters showed an excellent fit with the equation; however, the actual loading factor (K) appears to be lower than would be predicted for the physical-chemical properties of toluene.

The adsorption isotherm data indicate that activated carbon could be used to remove PAH compounds from aqueous wastes. However, relatively high dosages of activated carbon would be required to remove the five-membered aromatic ring compounds such as chrysene and benzo(a)pyrene. For example, as calculated from the Freundlich equation, it would require 1,667 mg/l of activated carbon to reduce the concentration of chrysene from 0.01 mg/l to 0.0001 mg/l in a single-stage contactor.

ON-SITE EVALUATIONS OF PILOT-SCALE DUAL MEDIA-ACTIVATED CARBON TREATMENT SYSTEMS FOR REMOVAL OF TOXIC CONTAMINANTS FROM PETROLEUM REFINERY WASTEWATER

The aerated lagoon treatment system at the oil refinery where the pilot systems were evaluated produces a good quality effluent with respect to chemical criteria as specified in the NPDES effluent guidelines. The concentration of chemical contaminants in the final effluent indicated that the effluent was of good quality throughout this study.

If fish toxicity were used as the criterion for indicating quality of the final effluent, the effluent would be of somewhat lower quality than that indicated by chemical criteria. The total cumulative mortality of the fathead minnows exposed to the normal lagoon treated effluent for 32 days was 25% (Table 3). In contrast, no mortality was observed during the 32-day exposure of the fathead minnows to the pilot-scale aquaculture and DM-AC treatment systems. Although the normal lagoon treated oil refinery wastewater would not have caused any measurable acutely toxic effects to fathead minnows in a standard 96-hour fathead minnow bioassay, it was lethal to 25% of the test fish after 32 days of exposure to the undiluted effluent. The first mortality was observed on day 1 . Both of the pilot-scale advanced treatment

systems, aquaculture and dual media-activated carbon, significantly improved the oil refinery wastewater with respect to acute toxicity to the fathead minnows.

TABLE 3. PERCENT MORTALITY OF FATHEAD MINNOWS (Pimephales promelas) AFTER 32 DAYS CONTINUOUS EXPOSURE TO NORMAL AERATED LAGOON, PILOT-SCALE AQUACULTURE AND PILOT-SCALE DUAL MEDIA-ACTIVATED CARBON (DM-AC) TREATED OIL REFINERY WASTEWATER

	Treatment System		
Days of exposure	Aerated lagoon	Aquaculture	DM-AC
	Percent mortality of replicates		
9/18/78 Start	0	0	0
8	0	0	0
11	0	0	0
16	10%	0	0
22	5%	0	0
24	0	0	0
29	5%	0	0
32	5%	0	0
Total cumulative mortality	25%	0	0

Response of benthic macroinvertebrate populations exposed to the three effluents also indicated that the aquaculture and DM-AC pilot-scale systems significantly improved the aerated lagoon effluent with respect to effects on macroinvertebrate organisms. Although there was no significant difference in the diversity index of organisms exposed to the three effluents, the number of species and mean density of benthic macroinvertebrates was higher after 32 days of exposure to the two pilot-scale treated effluents than that of the aerated lagoon effluent (Table 4). The mean density was over 100% higher. As in the case of fish mortality, effects were not observed until after 16 days of exposure. Species lists of benthic macroinvertebrates are presented in Appendix C.

TABLE 4. RESPONSE OF BENTHIC MACROINVERTEBRATE ORGANISMS TO SELECTIVELY TREATED OIL REFINERY WASTEWATER

		Species diversity (d)			Number of species			Mean density		
Date		B	C	D	B	C	D	B	C	D
9/18/78	(0)	3.4	3.4	3.4	44	44	44	2243	2243	2243
9/26/78	(8)	3.6	3.6	3.5	38	35	44	2985	1804	3868
10/04/78	(16)	2.4	3.1	2.9	39	40	41	5219	5262	6226
10/20/78	(32)	2.5	2.0	1.8	22	39	36	4689	10113	12352

B=normal aerated lagoon treatment system; C=pilot-scale aquaculture treatment system; D=pilot-scale dual media-activated carbon treatment system.

The index of similarity showed that the species composition of the benthic macroinvertebrate assemblages exposed to the pilot-scale aquaculture and DM-AC treated wastewaters were very similar (Table 5). In contrast, the species composition of the benthic macroinvertebrate assemblages after 32-day exposure to the normal aerated lagoon treated wastewater was not similar to the assemblages of benthic macroinvertebrate organisms exposed to the effluents from the two pilot-scale advanced wastewater treatment systems. These differences became apparent on day 16 of the study.

TABLE 5. INDEX OF SIMILARITY OF ASSEMBLAGES OF BENTHIC MACROINVERTEBRATE ORGANISMS EXPOSED TO SELECTIVELY TREATED OIL REFINERY EFFLUENTS

	B vs C	B vs D	C vs D
8 day	70.57	86.89	69.56
16 day	61.10	57.27	83.48
32 day	59.11	57.29	84.90

B = normal aerated lagoon treatment system
C = pilot-scale aquaculture treatment system
D = pilot-scale dual media-activated carbon treatment system

A number of chemical parameters were measured periodically during the study to determine if, and to what extent, add-on pilot-scale aquaculture and DM-AC treatment would further reduce concentrations of these parameters found in the aerated lagoon effluent. Additional reduction of a parameter by one or both of the pilot systems appears to be a function of the parameter itself.

The 5-day BOD of the normal aerated lagoon treated oil refinery wastewater varied from 15.8 to 29.7 mg/l (mean of 20.2 mg/l) (Table 6). The pilot-scale aquaculture system reduced the mean 5-day BOD concentration by 59.9% to 8.1 mg/l. The pilot-scale DM-AC system removed an average of 50.9 of additional 5-day BOD demand from the normal aerated lagoon treated system. Therefore, the pilot-scale aquaculture system removed slightly more 5-day BOD than did the DM-AC treatment system.

TABLE 6. CONCENTRATION (mg/l) OF BOD IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18, 1978	21.0	7.8	14.8
Sep 26, 1978	15.8	10.2	9.3
Oct 04, 1978	17.8	9.2	3.1
Oct 12, 1978	16.9	5.7	8.0
Oct 20, 1978	29.7	7.6	14.1
$\bar{x}$	20.2	8.1	9.9
SD	5.6	1.7	4.8

The mean concentration of COD was 128.1 mg/1 for the aerated lagoon, 137.0 mg/1 for the pilot-scale aquaculture, and 31.4 mg/1 for the pilot-scale DM-AC treatment system (Table 7). The mean concentration of total TOC was 45.1 mg/1 for the aerated lagoon, 46.9 mg/1 for the pilot-scale aquaculture, and 11.2 mg/1 for the pilot-scale DM-AC treatment systems (Table 8). The COD and TOC data clearly show a significant reduction in concentration after the pilot-scale DM-AC treatment system. In contrast, the concentration of COD and TOC increased after the pilot-scale aquaculture system. The TOC and COD data indicate the rate of carbon fixation via photosynthetic activity of the phytoplankton and emergent vegetation in the pilot-scale aquaculture system was greater than the rate of biodegradation. Carbon fixation into algal cells could cause the observed increase in TOC and COD concentration. The algal cells would also result in an increase in 5-day BOD, but the total increase would not be as great since the algal cells would not be totally biodegraded in a 5-day BOD test.

TABLE 7. CONCENTRATION (mg/1) OF COD IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	131.4	141.0	47.2
Sep 26 78	127.9	142.1	37.4
Oct 4 78	130.2	146.8	25.2
Oct 12 78	128.1	135.8	21.3
Oct 20 78	123.0	119.3	26.0
$\bar{x}$	128.1	137.0	31.4
SD	3.2	10.6	10.7

TABLE 8. CONCENTRATION (mg/1) OF TOC IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	43.8	48.0	9.6
Sep 26 78	47.8	53.0	16.0
Oct 4 78	50.8	48.6	10.5
Oct 12 78	40.1	40.1	10.1
Oct 20 78	42.8	44.6	9.6
$\bar{x}$	45.1	46.9	11.2
SD	4.2	4.8	2.7

The concentration of nutrient chemicals was significantly reduced by the pilot-scale aquaculture treatment system but not by the DM-AC treatment system. The aquaculture system reduced the mean nitrate nitrogen concentration by 88% and the nitrite nitrogen concentration by 64% (Tables 9 and 10). The aquaculture removed 56% of the total phosphate phosphorus and 69% of the soluble phosphate phosphorus (Tables 11 and 12). The concentration of ammonia in the aerated lagoon treated effluent was too low to obtain any significant results (Table 13).

TABLE 9. CONCENTRATION (mg/1) OF NITRATE-NITROGEN IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	2.32	0.73	1.57
Sep 26 78	2.31	0.11	4.01
Oct 4 78	3.19	0.33	3.30
Oct 12 78	3.24	0.42	4.09
Oct 20 78	7.18	0.66	6.36
$\bar{x}$	3.65	0.45	3.87
SD	2.02	0.25	1.72

TABLE 10. CONCENTRATION (mg/1) OF NITRITE-NITROGEN IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	0.50	0.12	0.40
Sep 26 78	0.12	0.14	0.14
Oct 4 78	0.77	0.23	0.43
Oct 12 78	0.96	0.41	0.99
Oct 20 78	0.95	0.32	0.98
$\bar{x}$	0.66	0.24	0.59
SD	0.35	0.12	0.38

TABLE 11. CONCENTRATION (mg/1) OF TOTAL PHOSPHATE-PHOSPHORUS IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	0.239	0.027	0.237
Sep 26 78	0.146	0.068	0.132
Oct 4 78	0.241	0.174	0.145
Oct 12 78	0.255	0.120	0.246
Oct 20 78	-	-	-
$\bar{x}$	0.220	0.097	0.190
SD	0.005	0.006	0.006

TABLE 12. CONCENTRATION (mg/1) OF DISSOLVED PHOSPHATE-PHOSPHORUS IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	0.121	0.002	0.120
Sep 26 78	0.044	0.002	0.054
Oct 4 78	0.126	0.065	0.130
Oct 12 78	0.198	0.087	0.203
Oct 20 78	-	-	-
$\bar{x}$	0.122	0.038	0.127
SD	0.006	0.004	0.006

TABLE 13. CONCENTRATION (mg/1) OF AMMONIA NITROGEN IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	3.3	1.0	4.5
Sep 26 78	1.0	1.0	1.0
Oct 4 78	1.0	1.0	1.0
Oct 12 78	1.0	1.0	1.0
Oct 20 78	1.0	1.0	1.0
$\bar{x}$	0.66	1.0	1.0
SD	0.5	0	0

Several other chemical parameters were significantly affected by the aerated lagoon, pilot-scale aquaculture, and pilot-scale DM-AC treatment systems (Appendix B). There was an increase in concentration of total dissolved solids (Table B-1), reduction in suspended solids (Table B-2), and turbidity (Table B-3) in the pilot-scale treatment systems. The concentration increase of sodium (Table B-5), calcium (Table B-6) and chlorides (Table B-4) in the aquaculture treated wastewater was probably due to evaporative concentration.

The concentration of iron (Table B-9), lead (Table B-10), zinc (Table B-11), copper (Table B-12), chromium (Table B-13), cadmium (Table B-14), and manganese (Table B-15) may have been reduced by the pilot-scale aquaculture and DM-AC treatment systems, but not significantly.

Subjective visual observations of the artificial streams during the exposure indicated that the growth of attached algal filaments was more abundant in the aerated lagoon and DM-AC treated wastewaters than in the aquaculture treated wastewater.

The aquaculture system was as effective as the DM-AC system with respect to all parameters except TOC and COD. Adaptation of more effective biological filter-feeding organisms in the aquaculture system should improve the TOC and COD removal efficiencies. If that could be accomplished, then aquaculture systems could become a realistic alternative to dual media-activated carbon systems for advanced treatment or polishing of secondarily treated oil refinery wastewaters.

REFERENCES

Acheson, M. A., R. M. Harrison, R. Perry, and R. A. Wellings, 1976. Factors Affecting the Extraction and Analysis of Polynuclear Aromatic Hydrocarbons in Water. Water Research, 10:207-212.

Adams, A. D. 1974. Powdered carbon: Is It Really That Good? Water and Wastes Engineering, 11:88-811.

Birks, J. B. 1970. Photophysics of Aromatic Molecules. Wiley Interscience, New York, NY. 704 pp.

Borneff, J. and R. Fisher, 1963. Carcinogenic Substances in Water and Soil. Part XII. Polycyclic Aromatic Hydrocarbons in Surface Water. (Arch. Hyg. Bakt., 146:572-585) from Chem. Absts., 1963, 59:5604d.

Borneff, J. and H. Kunte, 1967. Carcinogenic Substances in Water and Soil. Part XIX. Effect of Wastewater Purification on Polycyclic Aromatic Compounds. (Arch. Hyg. Bakt., 151:202-210) from Chem. Absts., 1968, 68:6013g.

Borneff, J. and H. Kunte, 1969. Carcinogenic Substances in Water and Soil. Part XXVI. A Routine Method for the Determination of PAH in Water. (Arch. Hyg. Bakt., 153:220-229) from Chem. Absts., 1969, 71:73890r.

Brock, D. A. 1977. Comparison of Community Similarity Indexes. Jour. Water Pollut. Control Fed., 49:2488-2494.

Burks, S. L. and J. L. Wilhm, 1977. Bioassays with a Natural Assemblage of Benthic Macroinvertebrates. In: Aquatic Toxicology & Hazard Evaluation, ASTM STP 634, F. L. Mayer & J. L. Hamelink, Eds. American Society for Testing & Materials, 1977, pp. 127-136.

DeJohn, P. B. 1974. Factors to Consider when Selecting Granular Activated Carbon for Wastewater Treatment. In: Proc. 29th Annu. Purdue Indust. Waste Conf., Purdue Univ., Lafayette, Ind. pp. 790-805.

DeJohn, P. B., and A. D. Adams, 1975. Activated Carbon Improves Wastewater Treatment. Hydrocarbon Processing, 54(10):104.

Dobbs, R. A., R. S. Middendorf, and S. M. Cohen, 1978. Carbon Adsorption Isotherms for Toxic Organics. U.S. EPA, Cincinnati, Ohio.

Engineering Science. 1975. Water Pollution Technology: Costs and Capabilities. Report No. PB-243 830-01 (NTIS).

Environmental Protection Agency. 1977. Sampling and Analysis Procedures for Screening of Industrial Effluents for Priority Pollutants. Environmental Monitoring & Support Laboratory, Cincinnati, OH.

Grieves, C. G., M. K. Stenstrom, J. D. Walk, and J. F. Grutsch, 1977. Effluent Quality Improvement by Powdered Activated Carbon in Refinery activated Sludge Processes. Presented at 42nd Midyear Meeting of the Amer. Petrol. Inst. Refining Dept., Chicago, Ill. Preprint No. 28-77. 26 pp.

Grieves, C. G., L. W. Crame, D. G. Venardos, and W. Ying, 1978. Powdered Carbon Enhancement versus Granular Carbon Adsorption for Oil Refinery BATEA Wastewater Treatment. Presented at 51st Annu. Conf. Water Poll. Contr. Fed., Anaheim, Calif. 24 pp.

Hager, D. G. 1974. Industrial Wastewater Treatment by Granular Activated Carbon. Industrial Water Engineering. Jan/Feb, 15 pp.

Hassler, J. W. 1963. Activated Carbon. Chemical Publishing Co., New York.

Hester, F. E. and J. S. Dendy, 1962. A Multiple-plate Sampler for Aquatic Macroinvertebrates. Trans. Amer. Fish. Soc. 91:420-421.

Kunte, H. 1967. Carcinogenic Substances in Water and Soil. Part XVIII. Determination of Polycyclic Aromatic Hydrocarbons by Mixed Thin-layer Chromatography and Fluorescence. (Arch. Hyg. Bakt., 151:193-201) from Chem. Absts. 1968, 68:93439s.

Laven, A. W. 1974. Activated Carbon Regeneration Perspectives. Amer. Inst. of Chem. Engineers Symposium Series, Vol. 70(144). pp. 285-295.

Loop, G. C. 1975. Refinery Effluent Water Treatment Plant using Activated Carbon. EPA-660/2-75-020. 100 pp.

Margalef, R. 1957. Information Theory in Ecology. General Systems 3:36-71. (English translation by W. Hall).

Mason, W. T., Jr., C. I. Weber, P. A. Lewis, and E. C. Julian, 1973. Factors Affecting the Performance of Basket and Multiplate Macroinvertebrate Samples. Freshwater Biol. 3:409-436.

McCrodden, B. A. 1975. Treatment of Refinery Wastewater using Filtration and Carbon Adsorption. Paper presented at Technology Transfer Conference, Activated Carbon in Water Pollution Control, sponsored by Environment Canada, the Pollution Control Association of Ontario, and the Canadian Society for Chemical Engineering, Oct. 1975. In: Matthews, J. E. 1978. Treatment of Petroleum Refinery, Petrochemical and Combined Industrial-municipal Wastewaters with Activated Carbon. EPA-600/2-78-200. p. 17.

McKay, J. F. and D. R. Latham, 1972. Fluorescence Spectrometry in the Characterization of High-boiling Petroleum Distillates. Analyt. Chem., 44:2132-2136.

Nakajima, A. 1977. Fluorescence Spectra of Condensed Aromatic Hydrocarbons in Water and in Aqueous Surfactant Solution. Photochem. & Photobiol., 25:593-598.

Paulson, E. G. 1970. Activated Carbon Chains Effluents. Oil & Gas Jour. 68(26):85-87.

Puri, B. R. 1970. Surface Complexes on Carbons. In: Chemistry and Physics of Carbon, edited by P. L. Walker. Marcel Dekker, Inc. New York.

Pyriki, C. and W. Moldenhauer, 1959. Filter Cigarets. Chem. Absts., 1960, 54:3865a.

Reichert, J., H. Kunte, K. Engelhardt, and J. Borneff, 1971. Carcinogenic Substances Occurring in Water and Soil. Part XXVII. Further Studies on the Elimination from Wastewater of Carcinogenic Polycyclic Aromatic Hydrocarbons. (Arch. Hyg. Bakt., 155:18-40) from Chem. Absts., 1971, 75:154806c.

Rizzo, J. A. 1976. Case History: Use of Powdered Activated Carbon in an Activated Sludge System. In: Proc. of Open Forum on Management of Petrol. Refinery Wastewaters, Presented by U.S. EPA, A.P.I., Nat'l. Petrol. Refiners Assoc., Univ. of Tulsa, Jan. 1976. pp. 359-374.

Sawicki, E., T. R. Hauser, and T. W. Stanley, 1960. Ultraviolet, Visible and Fluorescence Spectral Analysis of Polynuclear Hydrocarbons. Inter. J. Air Pollut., 2:253.

Sawicki, E. 1970. Tentative Method of Analysis for Polynuclear Aromatic Hydrocarbon Content of Atmospheric Particulate Matter. Health Lab. Sci., 7:31-44.

Sawicki, E. 1970. Tentative Method of Microanalysis for 3,4-benzpyrene in Airborne Particulates and Source Effluents. Health Lab. Sci., 7:56-59.

Shell, S. L., J. L. Boyd, and D. A. Dahlstrom, 1971. Upgrading Waste Treatment Plants. Chem. Eng. 78(14):97-102.

Smith, J. L., and R. A. Leone, 1975. Water Pollution Control Act of 1972. Economic Impacts. Petroleum Refinery Industry. 232 pp.

Thomas, J. F., B. D. Tebbens, E. N. Sanborn, and J. Cripps, 1960. Fluorescent Spectra of Aromatic Hydrocarbons found in Polluted Atmospheres. Inter. J. Air Pollut., 2:210-220.

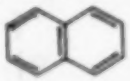
Weber, C. I. 1973. Biological Field and Laboratory Methods. Environmental Protection Agency. Cincinnati, Ohio.

APPENDIX A
CARBON ADSORPTION ISOTHERM DATA

TABLE A-1. CARBON ADSORPTION ISOTHERM DATA FOR NAPHTHALENE

COMPOUND: Naphthalene

FORMULA: $C_{10}H_8$

STRUCTURE: 

MOLECULAR WEIGHT: 128.16

FREUNDLICH PARAMETERS

$\frac{M}{}$	C_f	$X=C_o-C_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.0	291.71	0.00	
1.0	222.69	69.02	69.02
2.5	158.22	133.49	53.40
5.0	70.99	220.72	44.14
10.0	24.95	266.76	26.68
25.0	3.15	288.56	11.54

$K = 123.32$

$\frac{1}{n} = 0.41$

Correlation coefficient (r) = 0.997

TABLE A-2. ADSORPTION CAPACITY OF CARBON FOR NAPHTHALENE

INITIAL CONCENTRATION mg/l	ADSORPTION CAPACITY mg/g
1.0	123.32
0.1	47.88
0.01	18.49
0.001	7.22

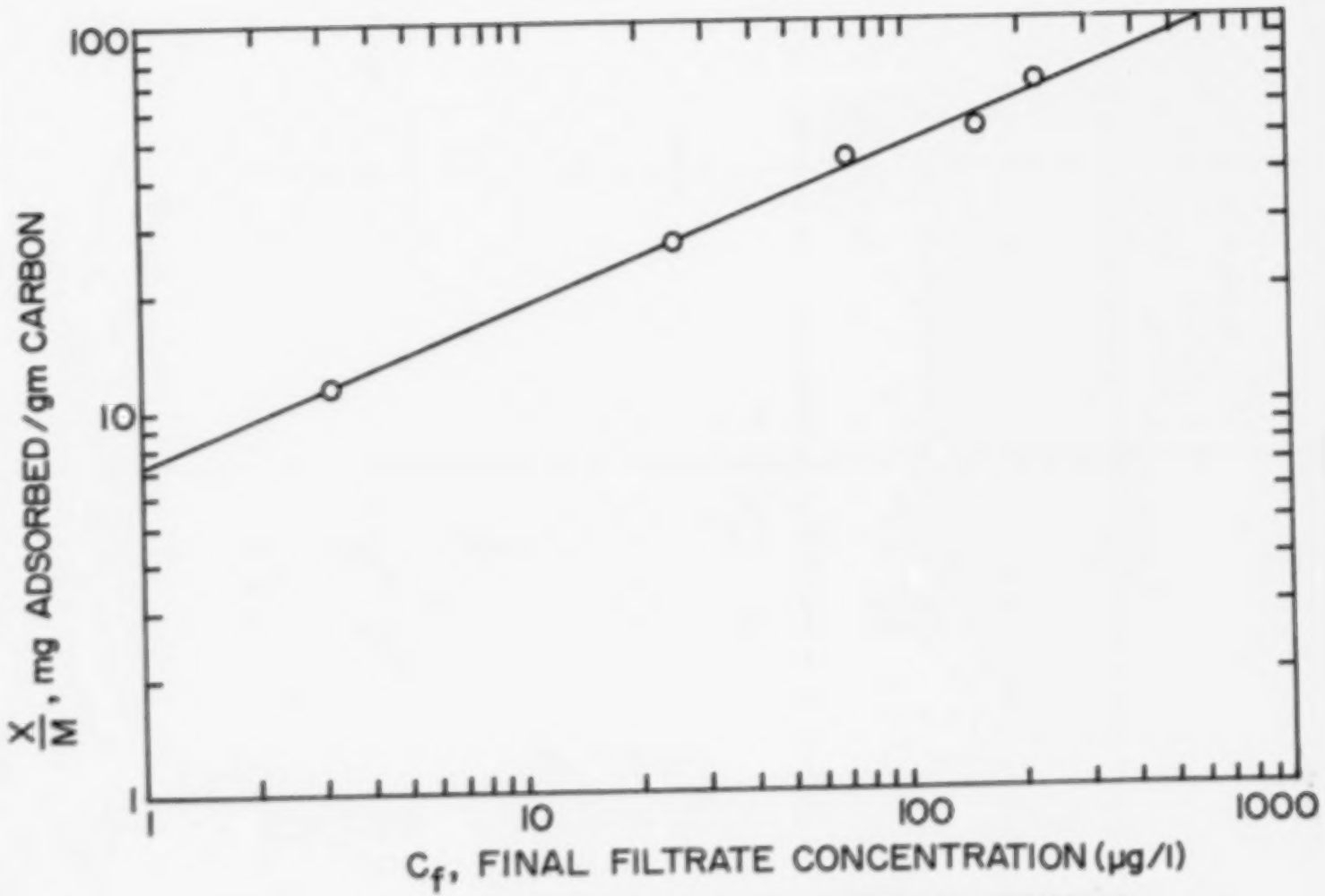
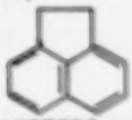


Figure 1. Carbon adsorption isotherm for naphthalene.

TABLE A-3. CARBON ADSORPTION ISOTHERM DATA FOR ACENAPHTHENE

COMPOUND: Acenaphthene

FORMULA: $C_{12}H_{10}$

STRUCTURE: 

MOLECULAR WEIGHT: 154.21

FREUNDLICH PARAMETERS

M	C_f	$X=C_o-C_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.0	290.70	0.00	
1.0	224.29	66.41	66.41
2.5	147.76	142.94	57.18
5.0	55.43	235.27	47.05
10.0	15.11	275.59	27.56
25.0	4.77	285.93	11.44

K = 140.50

$\frac{1}{n}$ = 0.43

Correlation coefficient (r) = 0.9721

TABLE A-4. ADSORPTION CAPACITY FOR ACENAPHTHENE

INITIAL CONCENTRATION mg/l	ADSORPTION CAPACITY mg/g
1.0	140.50
0.1	51.68
0.01	19.01
0.001	6.99

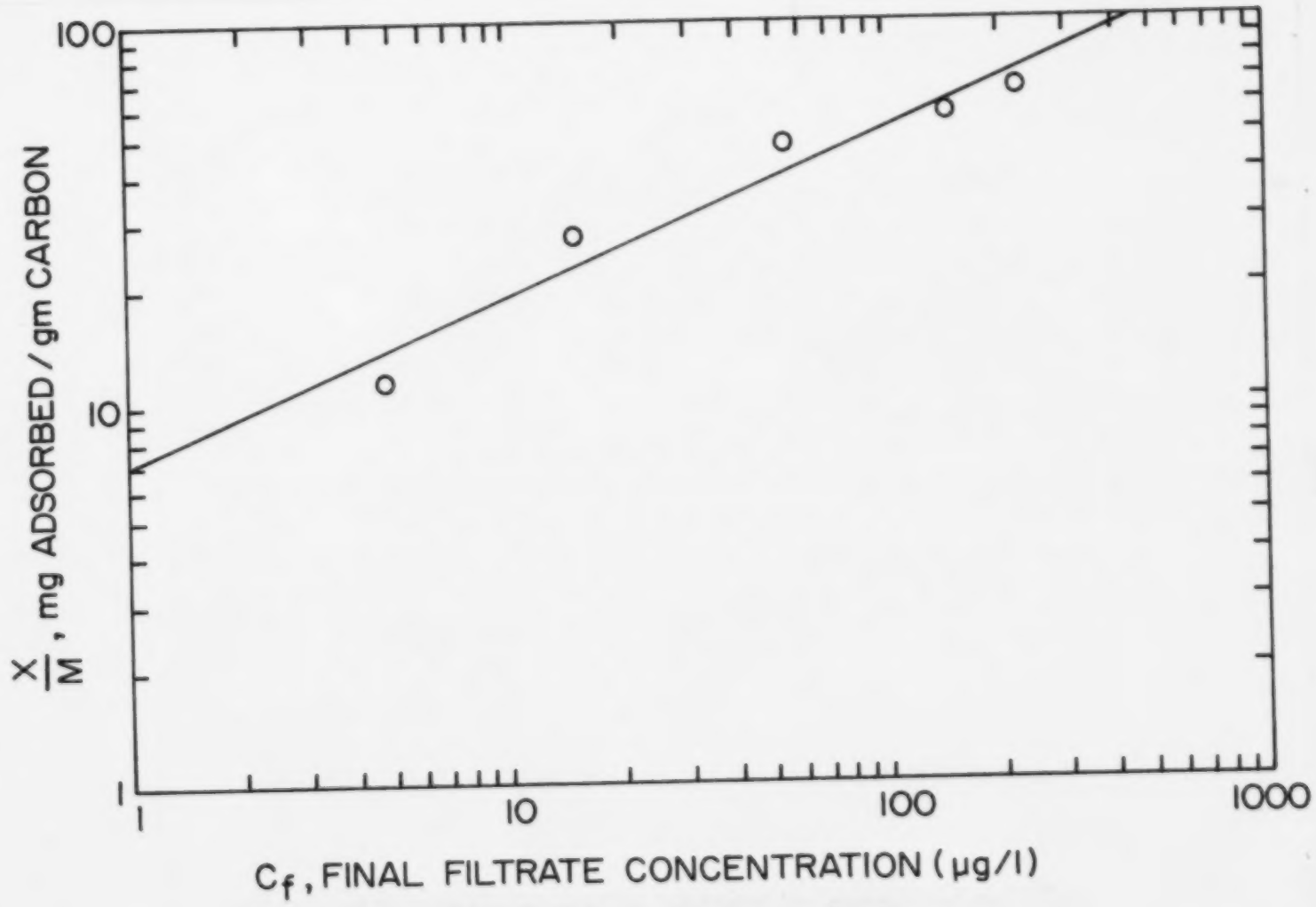
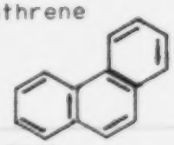


Figure 2. Carbon adsorption isotherm for acenaphthalene.

TABLE A-5. CARBON ADSORPTION ISOTHERM DATA FOR PHENANTHRENE

COMPOUND: Phenanthrene

FORMULA: $C_{14}H_{10}$

STRUCTURE: 

MOLECULAR WEIGHT: 178.22

FREUNDLICH PARAMETERS

M	C_f	$X=C_o-C_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.0	303.27	0.00	
1.0	245.06	58.21	58.21
2.5	155.48	147.79	59.12
5.0	55.17	248.10	49.62
10.0	16.28	286.99	28.70
25.0	10.36	292.91	11.72

$K = 134.57$

$\frac{1}{n} = 0.45$

Correlation coefficient (r) = 0.8944

TABLE A-6. ADSORPTION CAPACITY OF CARBON FOR PHENANTHRENE

INITIAL CONCENTRATION mg/l	ADSORPTION CAPACITY mg/g
1.0	134.57
0.1	48.04
0.01	17.15
0.001	6.12

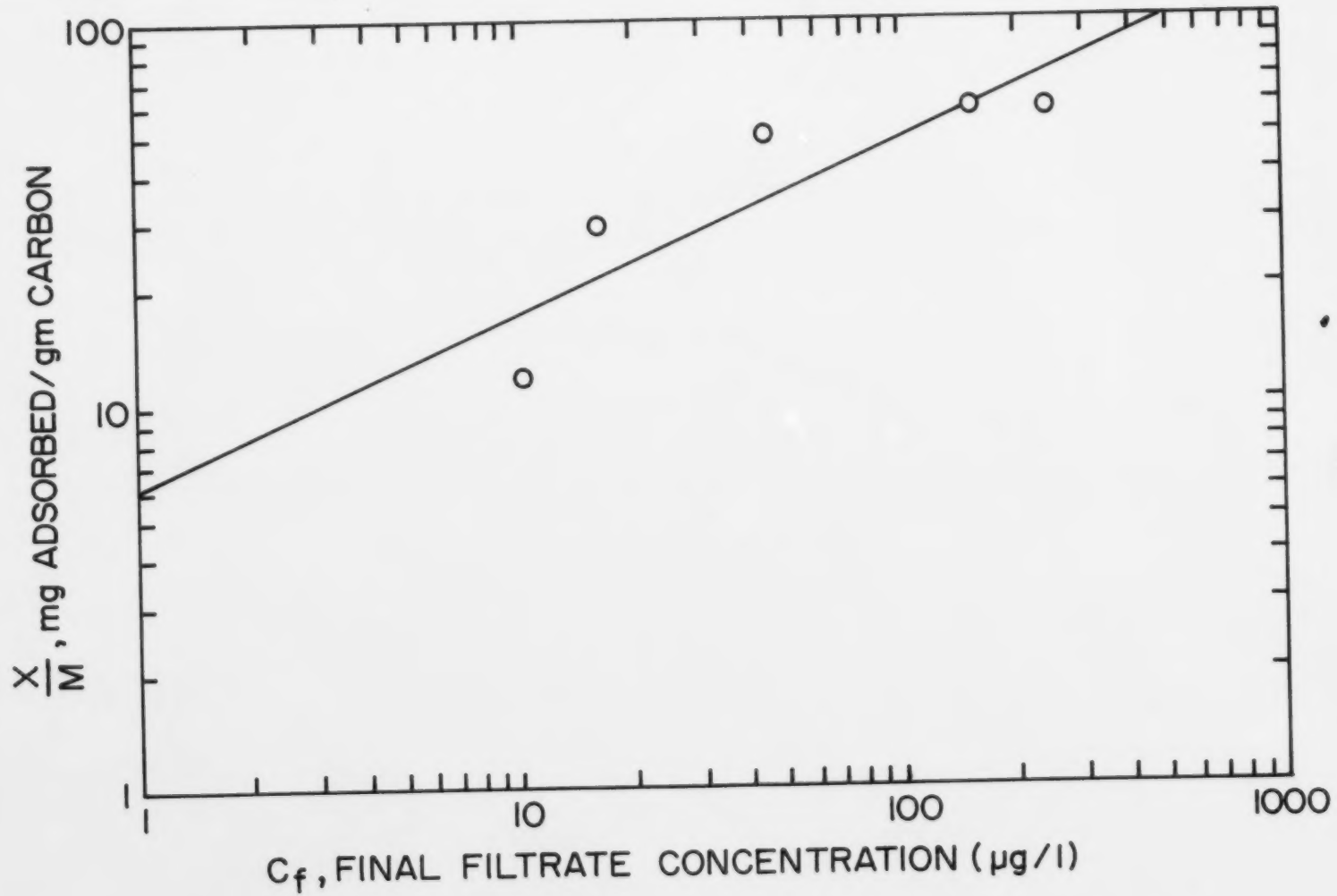
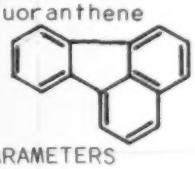


Figure 3. Carbon adsorption isotherm for phenanthrene.

TABLE A-7. CARBON ADSORPTION ISOTHERM DATA FOR FLUORANTHENE

COMPOUND: Fluoranthene FORMULA:

STRUCTURE:  MOLECULAR WEIGHT: 202.26

FREUNDLICH PARAMETERS

M	C_f	$X=C_o-C_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.0	261.72	0.00	
1.0	229.58	32.14	32.14
2.5	133.43	128.29	51.32
5.0	53.18	208.54	41.71
10.0	20.90	240.82	24.08
25.0	7.94	253.78	10.15

$K = 88.06$

$\frac{1}{n} = 0.38$

Correlation coefficient (r) = 0.821

TABLE A-8. ADSORPTION CAPACITY OF CARBON FOR FLUORANTHENE

INITIAL CONCENTRATION mg/l	ADSORPTION CAPACITY mg/g
1.0	88.06
0.1	36.68
0.01	15.28
0.001	6.36

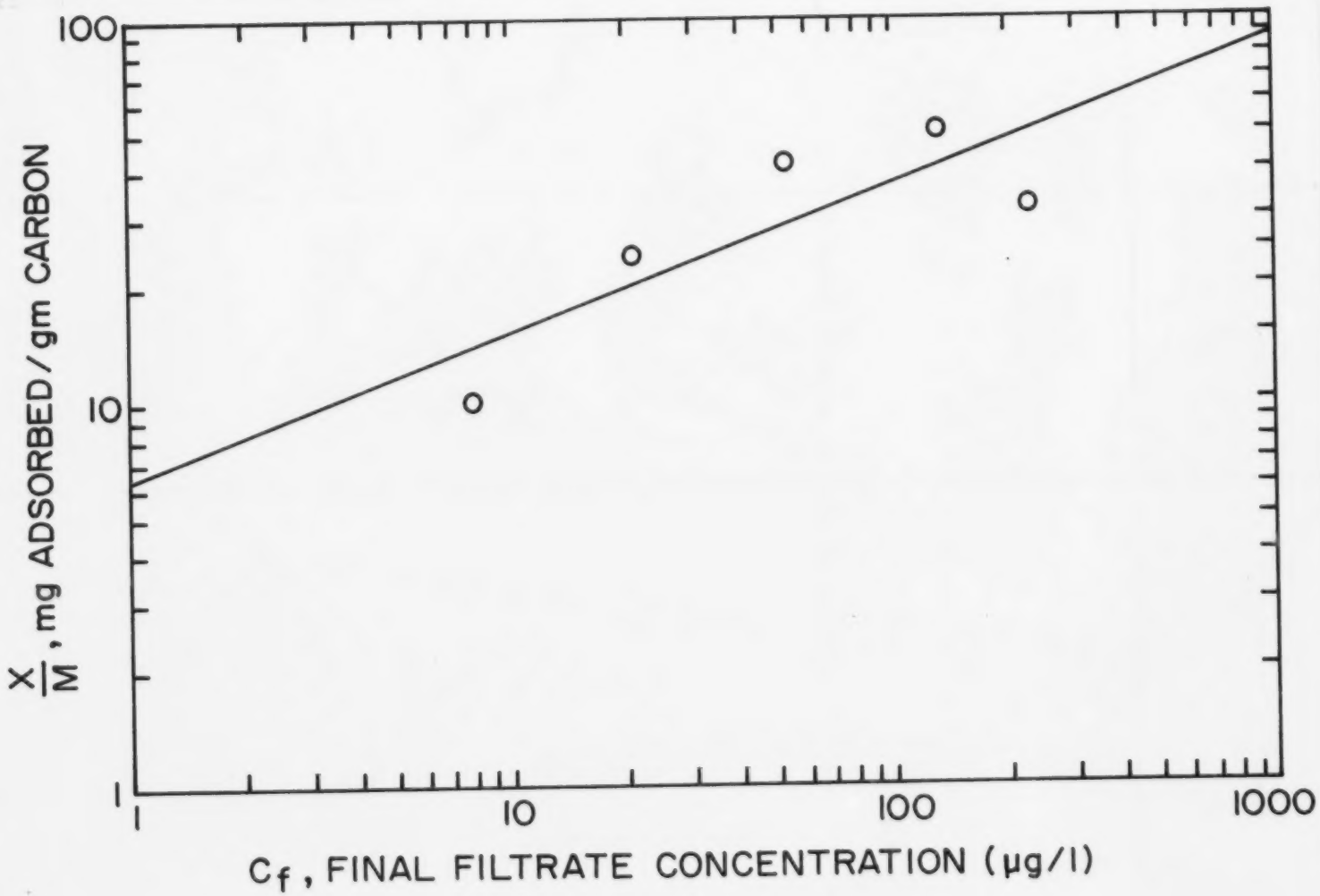
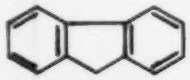


Figure 4. Carbon adsorption isotherm for fluoranthene.

TABLE A-9. CARBON ADSORPTION ISOTHERM DATA FOR FLUORENE

COMPOUND: Fluorene

FORMULA: $C_{13}H_{10}$

STRUCTURE: 

MOLECULAR WEIGHT: 166.21

FREUNDLICH PARAMETERS

M	C_f	$X=C_o-C_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.0	286.58		
1.0	213.32	73.26	73.26
2.5	132.01	154.57	61.83
5.0	62.61	223.97	44.79
10.0	17.13	269.45	26.95
25.0	11.17	275.41	11.02

K = 195.8

$\frac{1}{n}$ = 0.57

Correlation coefficient (r) = 0.949

TABLE A-10. ADSORPTION CAPACITY OF CARBON FOR FLUORENE

INITIAL CONCENTRATION mg/l	ADSORPTION CAPACITY mg/g
1.0	195.80
0.1	52.89
0.01	14.28
0.001	3.86

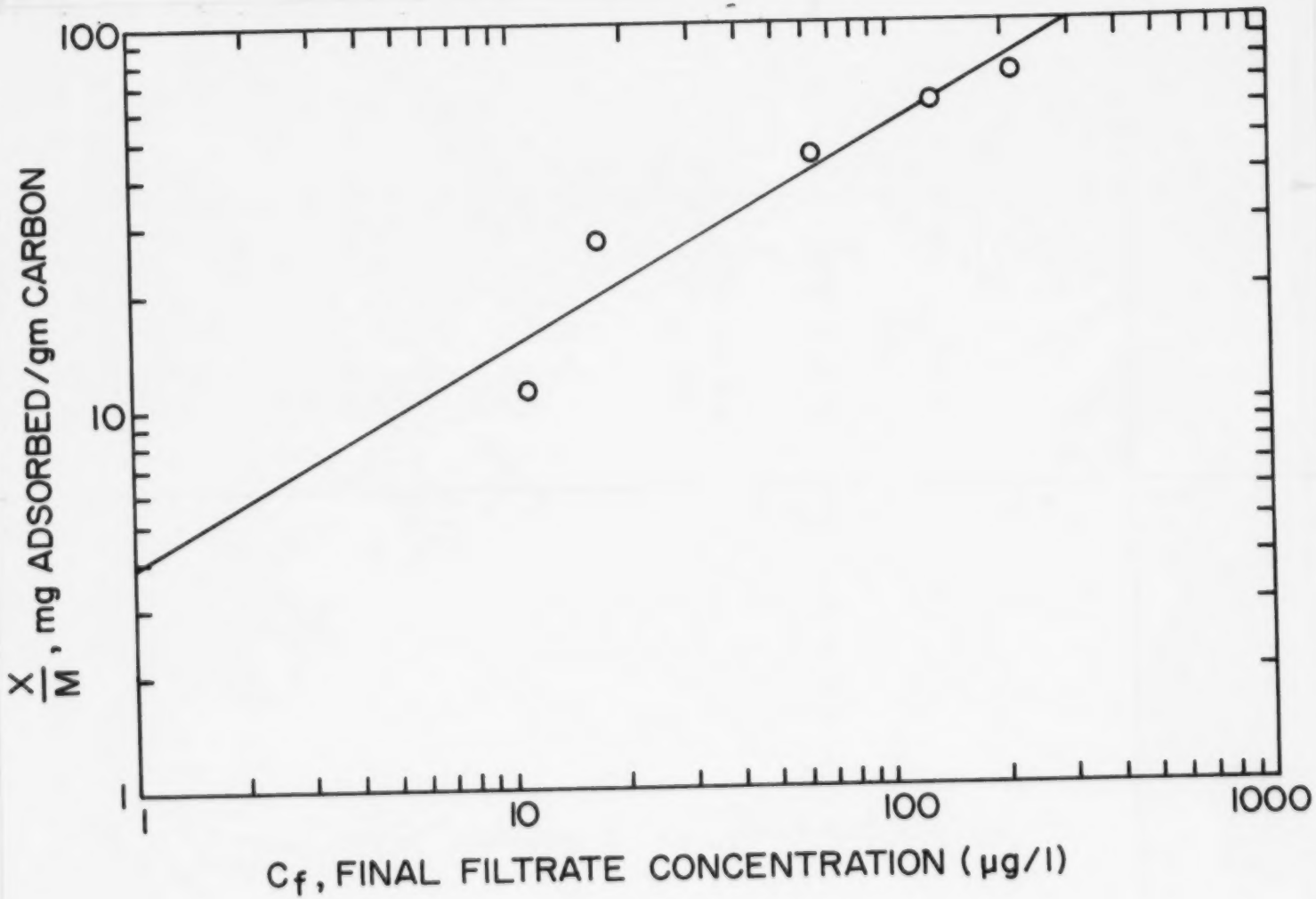
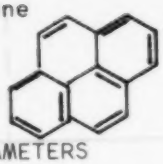


Figure 5. Carbon adsorption isotherm for fluorene.

TABLE A-11. CARBON ADSORPTION ISOTHERM DATA FOR PYRENE

COMPOUND: Pyrene

FORMULA: $C_{16}H_{10}$

STRUCTURE: 

MOLECULAR WEIGHT: 202.24

FREUNDLICH PARAMETERS

M	C_f	$X=C_oC_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.0	138.15	0.00	
1.0	105.32	32.83	32.83
2.5	49.06	89.09	35.64
4.0	24.22	113.93	28.48
6.0	5.73	132.42	22.07
10.0	2.72	135.43	13.54

K = 65.55

$\frac{1}{n}$ = 0.24

Correlation coefficient (r) = 0.925

TABLE A-12. ADSORPTION CAPACITY OF CARBON FOR PYRENE

INITIAL CONCENTRATION mg/l	ADSORPTION CAPACITY mg/g
1.0	65.55
0.1	37.78
0.01	21.77
0.001	12.55

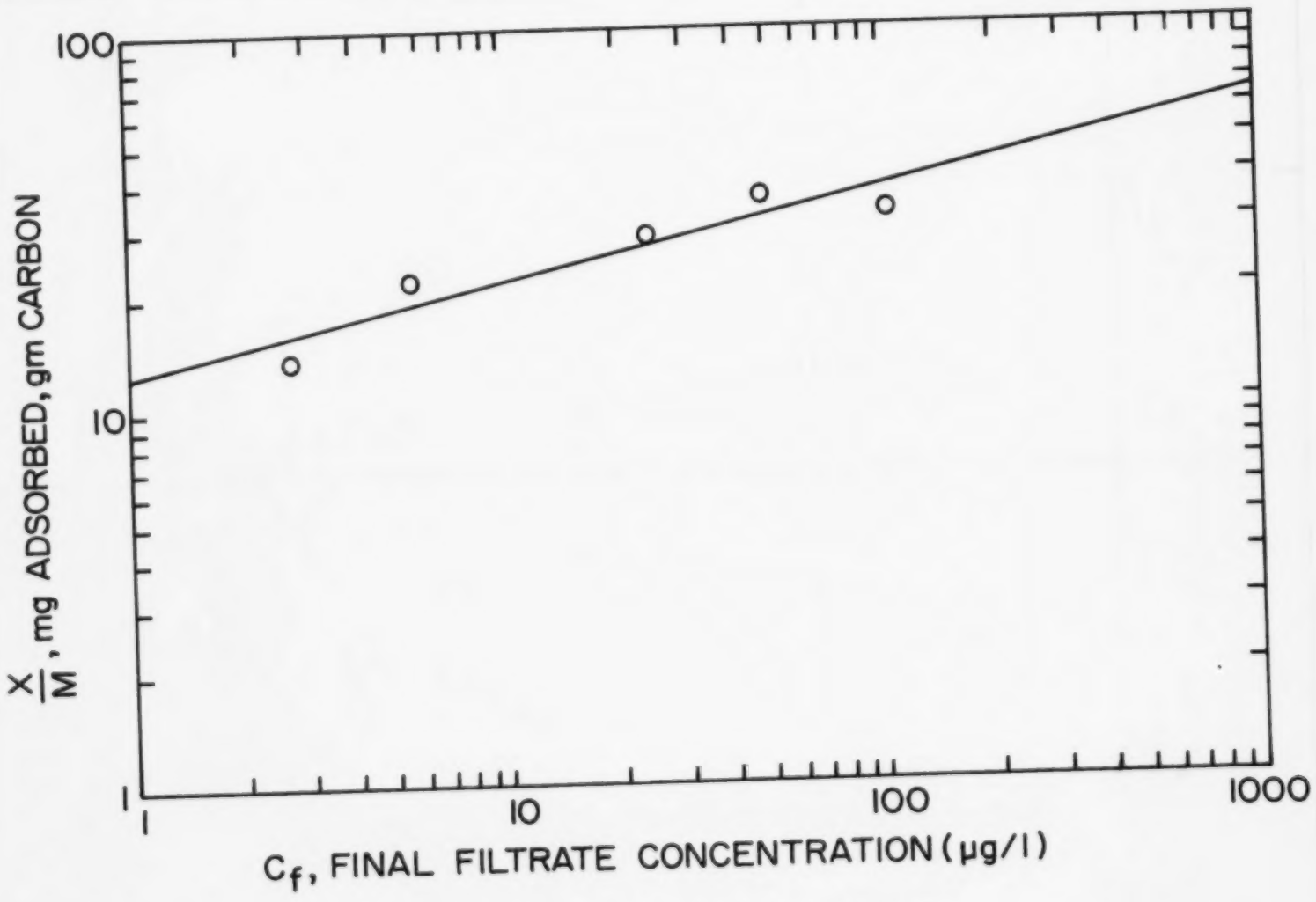
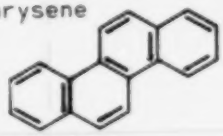


Figure 6. Carbon adsorption isotherm for pyrene.

TABLE A-13. CARBON ADSORPTION ISOTHERM DATA FOR CHRYSENE

COMPOUND: Chrysene

FORMULA: $C_{18}H_{12}$

STRUCTURE: 

MOLECULAR WEIGHT: 228.28

FREUNDLICH PARAMETERS

M	C_f	$X=C_o-C_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.0	295.00	0.00	
5.0	274.81	20.19	4.038
10.0	262.97	32.03	3.203
25.0	238.64	56.36	2.254
50.0	173.34	121.66	2.433
75.0	145.81	149.19	1.989
SECOND RUN			
0.0	143.27	0.00	
5.0	131.97	11.30	2.260
10.0	110.12	33.15	3.315
25.0	108.99	34.28	1.371
50.0	63.48	79.79	1.596
75.0	41.72	101.55	1.354
100.0	38.56	104.71	1.047

$K = 6.068$

$\frac{1}{n} = 0.50$

Correlation coefficient (r) = 0.823

TABLE A-14. ADSORPTION CAPACITY OF CARBON FOR CHRYSENE

INITIAL CONCENTRATION mg/l	ADSORPTION CAPACITY mg/g
1.0	6.068
0.1	1.909
0.01	0.601
0.001	0.189

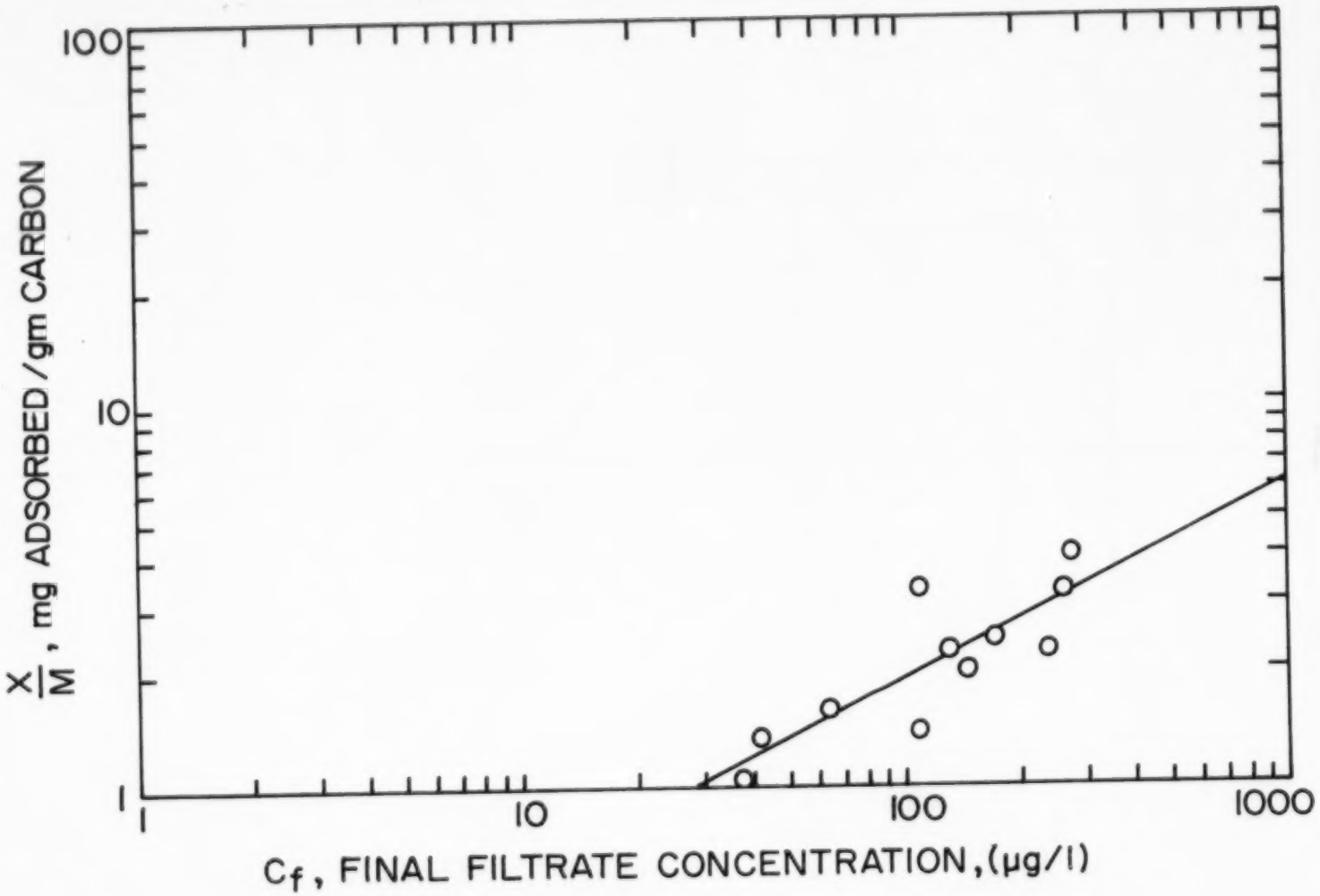
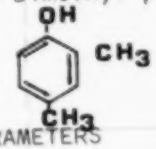


Figure 7. Carbon adsorption isotherm for chrysene.

TABLE A-15. CARBON ADSORPTION ISOTHERM DATA FOR 2,4 DIMETHYL PHENOL

COMPOUND: 2,4 Dimethyl phenol

FORMULA: $(CH_3)_2C_6H_3OH$

STRUCTURE: 

MOLECULAR WEIGHT: 122.17

FREUNDLICH PARAMETERS

M	C_f	$X=C_o-C_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.0	9,230.	0.	
7.5	7,310.	1,920.	256.
12.5	6,560.	2,670.	214.
25.0	4,290.	4,940.	198.
50.0	1,060.	8,170.	163.
75.0	6.	9,220.	123.

K = 184.27

$\frac{1}{n}$ = 0.09

Correlation coefficient (r) = 0.93

TABLE A-16. ADSORPTION CAPACITY OF CARBON FOR 2,4 DIMETHYL PHENOL

INITIAL CONCENTRATION mg/l	ADSORPTION CAPACITY mg/g
100.	335.24
10.	224.95
1.	184.27
0.1	150.95

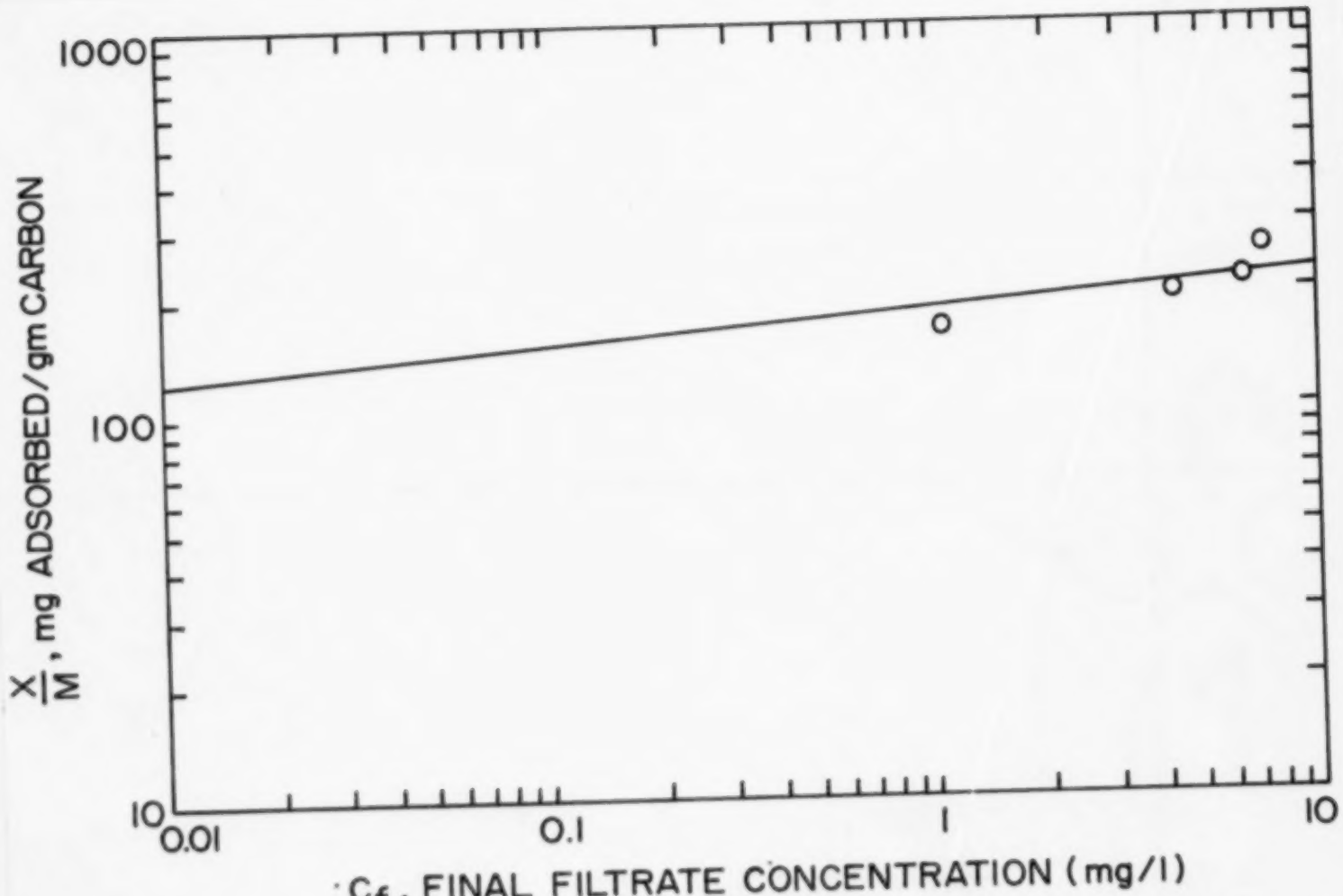
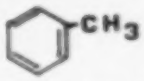


Figure 8. Carbon adsorption isotherm for 2,4-dimethylphenol.

TABLE A-17. CARBON ADSORPTION ISOTHERM DATA FOR TOLUENE

COMPOUND: Toluene

FORMULA: C_7H_8

STRUCTURE: 

MOLECULAR WEIGHT: 92.13

Activated Carbon: ICI Hydrodarco
FREUNDLICH PARAMETERS

M	C_f	$X=C_o-C_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.	3,870.	0.	
25.	2,200.	1,670.	67.
50.	1,520.	2,350.	47.
75.	1,300.	2,570.	34.
100.	620.	3,250.	32.
200.	100.	3,770.	19.

$K = 40.20.$

$\frac{1}{n} = 0.35$

Correlation coefficient (r) = 0.93

TABLE A-18. ADSORPTION CAPACITY OF CARBON FOR TOLUENE

INITIAL CONCENTRATION mg/l	ADSORPTION CAPACITY mg/g
100.	205.97
10.	90.99
1.	40.20
0.1	17.76

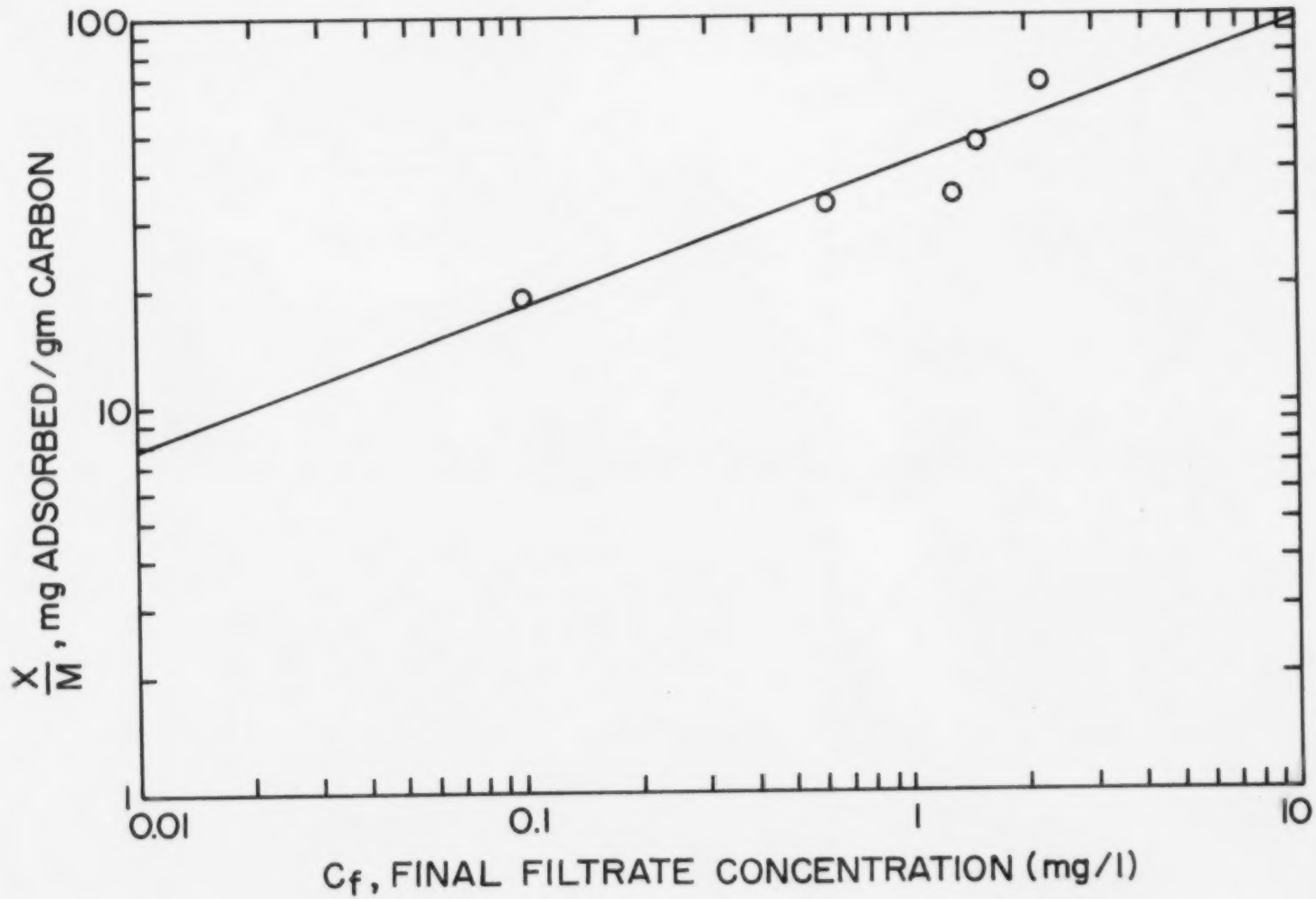
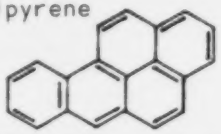


Figure 9. Carbon adsorption isotherm for toluene.

TABLE A-19. CARBON ADSORPTION ISOTHERM DATA FOR BENZO(A)PYRENE

COMPOUND: benzo(a)pyrene

FORMULA: $C_{20}H_{12}$

STRUCTURE: 

MOLECULAR WEIGHT: 252.3

FREUNDLICH PARAMETERS

M	C_f	$X=C_o-C_f$	$\frac{X}{M}$
CARBON DOSE mg	SOLUTE REMAINING IN SOLUTION ug	SOLUTE ADSORBED ug	mg/g
0.	237.38	0.	
10.	283.13	16.87	1.69
20.	274.26	25.74	1.29
40.	187.19	113.81	2.85
60.	91.83	208.17	3.47
75.	59.15	240.85	3.21
100.	12.46	287.54	2.88

K = Could not calculate.

$\frac{1}{n}$ = could not calculate

Correlation coefficient (r) = -0.5578

Linear Regression analysis of solute adsorbed (ug) versus dose of carbon (mg);

Y intercept (b) = -18.41
slope (m) = 3.29
correlation coefficient (r) = 0.984

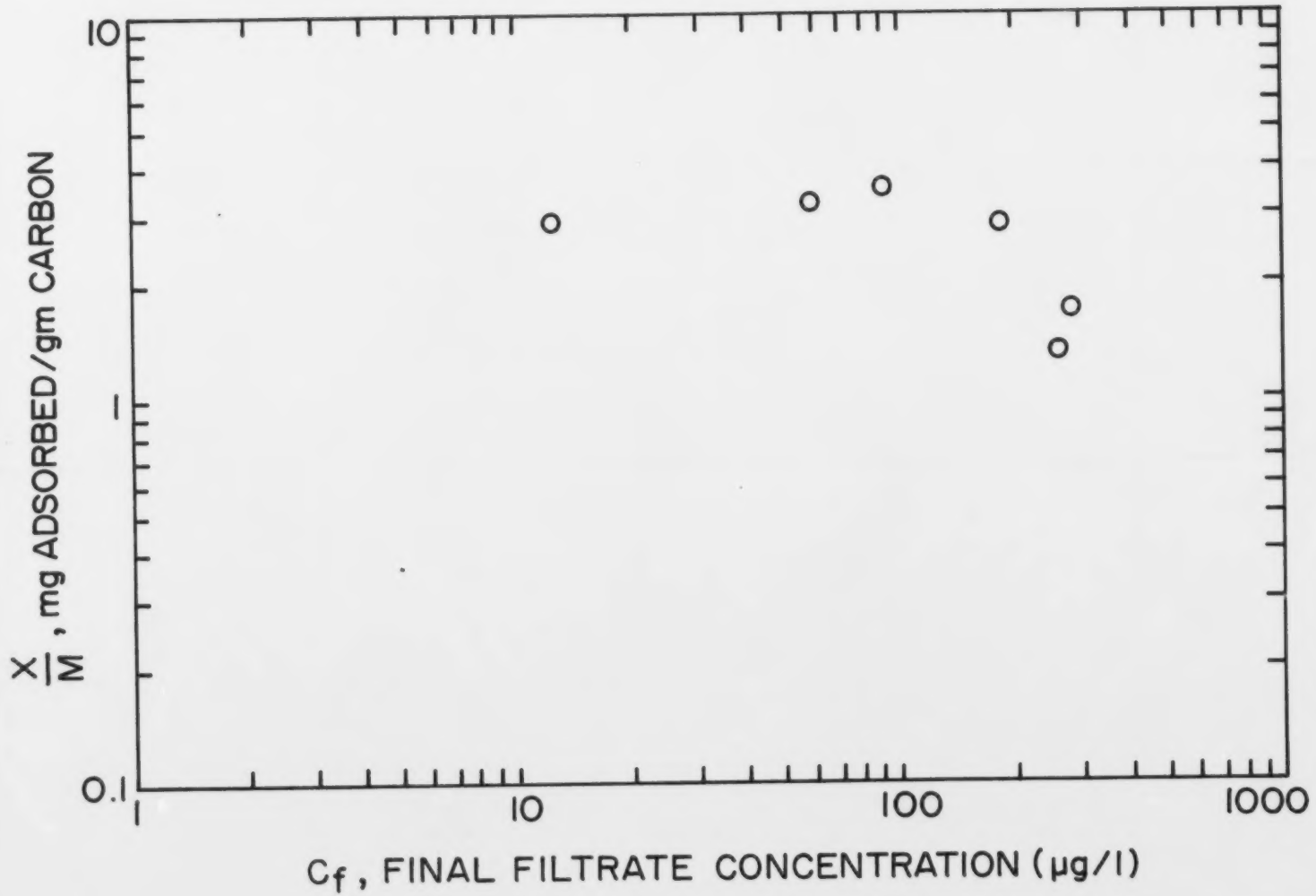


Figure 10. Carbon adsorption isotherm for benzo(a)pyrene.

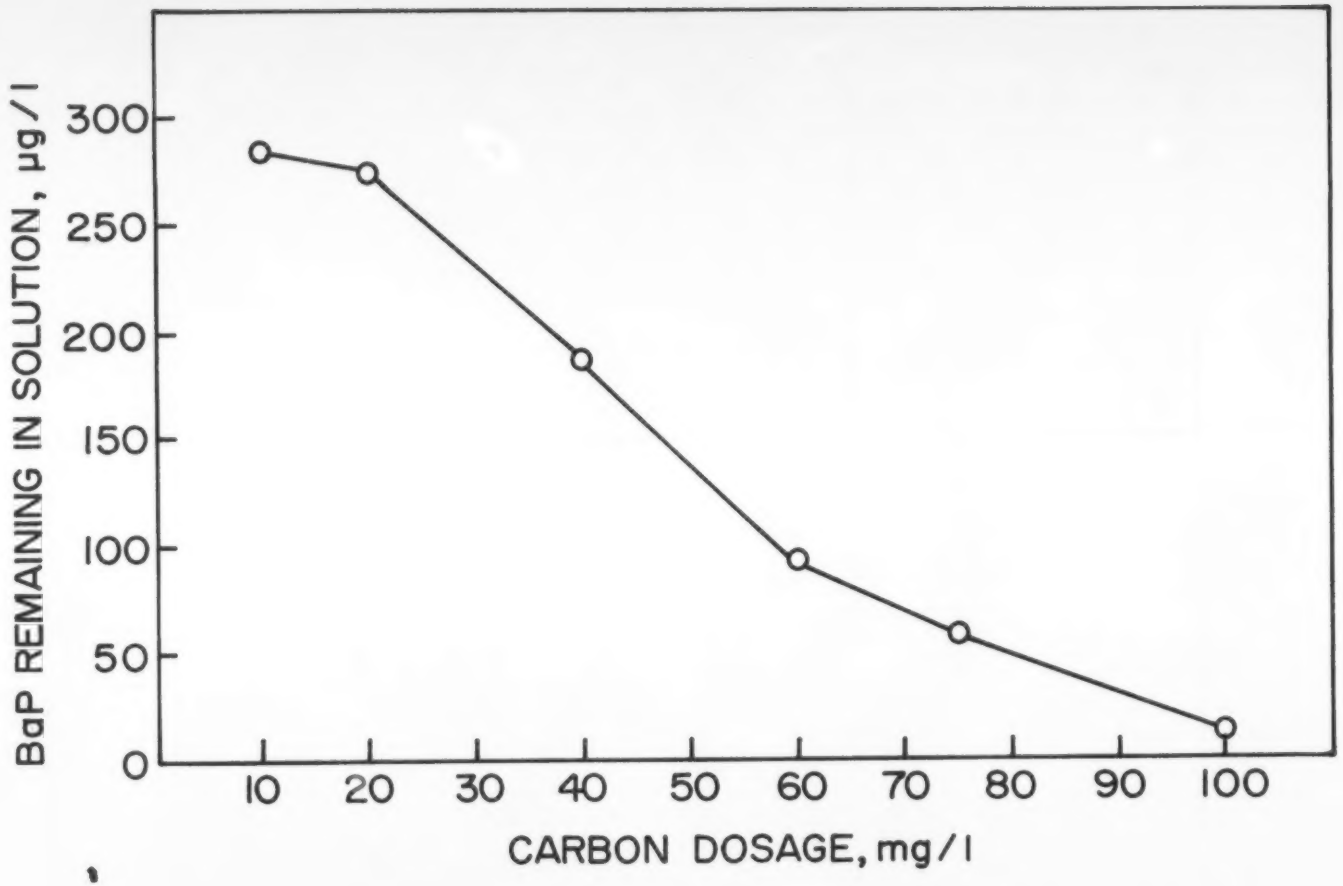


Figure 11. Quantity of benzo(a)pyrene remaining in solution at increasing levels of activated carbon.

APPENDIX B

CHEMICAL DATA FROM
ON-SITE EVALUATION OF
DUAL MEDIA-ACTIVATED CARBON AND
AQUACULTURE TREATMENT SYSTEMS FOR
REMOVAL OF TOXIC CONSTITUENTS FROM PETROLEUM REFINERY WASTEWATER

TABLE B-1. CONCENTRATION (mg/l) OF TOTAL DISSOLVED SOLIDS IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	2022	2244	2001
Sep 26 78	2116	2256	1999
Oct 4 78	1992	2284	1975
Oct 12 78	2056	2277	2043
Oct 20 78	2064	2236	2026
$\bar{x}$	2050	2259	2009
SD	46.7	20.7	26.3

TABLE B-2. CONCENTRATION (mg/l) OF SUSPENDED SOLIDS IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	41	31	30
Sep 26 78	30	23	23
Oct 4 78	33	21	14
Oct 12 78	22	10	11
Oct 20 78	40	8	12
$\bar{x}$	33	19	18
SD	7.8	9.6	8.2

TABLE B-3. CONCENTRATION (mg/l) OF TURBIDITY IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	77	84	44
Sep 26 78	92	102	58
Oct 4 78	85	70	28
Oct 12 78	80	54	43
Oct 20 78	82	47	41
$\bar{x}$	83	71	43
SD	5.7	22.3	10.7

TABLE B-4. CONCENTRATION (mg/l) OF CHLORIDE IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

Date	Aerated lagoon B	Aquaculture C	Activated carbon D
Sep 18 78	898	984	954
Sep 26 78	870	950	890
Oct 4 78	822	1000	860
Oct 12 78	755	870	760
Oct 20 78	856	945	900
$\bar{x}$	840	950	873
SD	54.9	50.2	71.6

TABLE B-5. CONCENTRATION (mg/l) OF SODIUM IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	435	4.2	447	3.9	473	2.7	483	4.2	435	4.2	445	4.3
Sep 26 78	438	2.0	473	3.1	501	2.6	495	2.5	438	2.1	432	2.2
Oct 4 78	420	1.8	432	1.9	457	1.8	505	2.4	426	2.0	432	2.0
Oct 12 78	426	1.1	413	1.2	464	1.9	476	1.9	426	1.4	420	1.4
Oct 20 78	516	1.8	522	1.5	566	1.0	570	1.7	503	1.5	507	1.7
$\bar{x}$	447	2.2	457	2.3	492	2.0	506	2.5	446	2.2	447	2.3
SD	39	1.2	42	1.1	44	0.69	38	.99	33	1.1	34	1.1

TABLE B-6. CONCENTRATION (mg/l) OF CALCIUM IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	97	1.0	93	1.0	90	1.0	93	1.0	97	1.3	97	1.0
Sep 26 78	97	1.0	95	1.0	92	1.0	95	1.0	92	1.0	92	1.0
Oct 4 78	86	1.0	90	1.0	92	1.0	99	1.0	88	1.0	90	1.0
Oct 12 78	110	1.0	110	1.0	118	1.0	118	1.0	110	1.0	110	1.0
Oct 20 78	108	1.0	118	1.0	121	1.0	121	1.0	120	1.0	120	1.0
$\bar{x}$	100	0	101	0	103	1.0	105	0	101	.26	102	0
SD	10	0	12	0	15	0	13	0	13	.58	13	0

TABLE B-7. CONCENTRATION (mg/l) OF MAGNESIUM IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	15	1.0	15	1.0	17	1.0	17	1.0	15	1.0	15	1.0
Sep 26 78	16	1.0	16	1.0	17	1.0	16	1.0	15	1.0	15	1.0
Oct 4 78	14	1.0	15	1.0	17	1.0	18	1.0	15	1.0	15	1.0
Oct 12 78	30	1.0	30	1.0	33	1.0	33	1.0	28	1.0	29	1.0
Oct 20 78	33	1.0	34	1.0	33	1.0	33	1.0	33	1.0	34	1.0
$\bar{x}$	22	0	22	0	23	0	23	0	21	0	22	0
SD	9	0	9	0	9	0	9	0	9	0	9	0

TABLE B-8. CONCENTRATION (mg/l) OF POTASSIUM IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	34	1.0	34	1.0	49	1.0	49	1.0	33	1.0	34	1.0
Sep 26 78	39	1.0	39	1.0	50	1.0	50	1.0	36	1.0	36	1.0
Oct 4 78	36	1.0	36	1.0	44	1.0	47	1.0	36	1.0	36	1.0
Oct 12 78	66	1.0	67	1.0	43	1.0	41	1.0	65	1.0	64	1.0
Oct 20 78	76	1.0	76	1.0	47	1.0	53	1.0	76	1.0	76	1.0
$\bar{x}$	50	0	50	0	47	0	48	0	49	0	49	0
SD	19	0	20	0	3	0	4	0	20	0	19	0

TABLE B-9. CONCENTRATION (mg/l) OF IRON IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	.04	.31	.09	.35	.31	.27	.04	.31	.62	.27	.04	.40
Sep 26 78	.04	.04	.04	.04	.04	.04	.40	.18	.04	.04	.04	.04
Oct 4 78	.23	.28	.14	.10	.04	.10	.04	.10	.09	.10	.09	.05
Oct 12 78	.85	.48	.66	.43	1.43	.04	.09	.04	.09	.10	.04	.05
Oct 20 78	1.95	.76	.76	.67	.19	.05	.14	.10	.28	.10	.28	.05
$\bar{x}$	.61	.37	.33	.32	.39	.09	.13	.14	.22	.12	.08	.12
SD	.82	.27	.35	.26	.59	.11	.16	.11	.24	.09	.12	.16

TABLE B-10. CONCENTRATION (mg/l) OF LEAD IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	.01	.01	.01	.01	.01	.01	.01	.02	.01	.01	.01	.08
Sep 26 78	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.02	.01
Oct 4 78	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01	.01
Oct 12 78	.04	.01	.03	.01	.02	.01	.01	.01	.01	.01	.01	.01
Oct 20 78	.08	.01	.02	.01	.01	.01	.01	.01	.01	.01	.01	.01
$\bar{x}$	.03	0	.01	.004	.004	0	0	.004	.002	0	.004	.02
SD	.03	0	.01	.005	.009	0	0	.009	.004	0	.009	.04

TABLE B-11. CONCENTRATION (mg/l) OF ZINC IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	.02	.01	.08	.02	.07	.07	.03	.04	.40	.17	.01	.01
Sep 26 78	.04	.01	.04	.01	.03	.01	.05	.02	.03	.01	.03	.01
Oct 4 78	.07	.01	.05	.01	.03	.01	.02	.01	.03	.01	.02	.01
Oct 12 78	.17	.03	.16	.03	.16	.01	.05	.01	.03	.01	.02	.01
Oct 20 78	.36	.02	.16	.02	.05	.01	.04	.02	.10	.02	.09	.01
$\bar{x}$	.13	.01	.10	.02	.07	.02	.04	.02	.12	.04	.03	.002
SD	.14	.01	.06	.01	.05	.03	.01	.02	.16	.07	.03	.004

TABLE B-12. CONCENTRATION (mg/l) OF COPPER IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	.04	.04	.04	.04	.05	.04	.04	.04	.33	.04	.02	.02
Sep 26 78	.04	.04	.04	.04	.05	.04	.04	.07	.04	.04	.04	.04
Oct 4 78	.04	.04	.04	.04	.04	.04	.04	.04	.04	.04	.04	.04
Oct 12 78	.04	.04	.04	.04	.04	.04	.04	.04	.04	.04	.04	.04
Oct 20 78	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05
$\bar{x}$	0	0	0	0	.02	0	0	.01	.07	0	0	0
SD	0	0	0	0	.03	0	0	.03	.15	0	0	0

TABLE B-13. CONCENTRATION (mg/l) OF CHROMIUM IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	.02	.02	.03	.02	.02	.02	.02	.02	.02	.02	.02	.02
Sep 26 78	.02	.02	.03	.02	.02	.02	.02	.02	.02	.02	.02	.02
Oct 4 78	.04	.02	.03	.02	.02	.02	.02	.02	.02	.10	.02	.02
Oct 12 78	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02
Oct 20 78	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02	.02
$\bar{x}$	.02	.004	.02	0	.004	0	.004	.004	.004	.02	0	0
SD	.01	.009	.01	0	.009	0	.009	.009	.009	.04	0	0

TABLE B-14. CONCENTATION (mg/l) OF CADMIUM IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
Sep 26 78	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
Oct 4 78	.001	.001	.001	.001	.001	.001	.001	.001	.001	.002	.003	.001
Oct 12 78	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
Oct 20 78	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001	.001
$\bar{x}$	0	0	0	.001	0	0	0	0	0	.001	.001	0
SD	0	0	0	.001	0	0	0	0	.001	.001	.002	0

TABLE B-15. CONCENTRATION (mg/l) OF MANGANESE IN CONVENTIONAL AERATED LAGOON, PILOT-SCALE AQUACULTURE, AND DUAL MEDIA-ACTIVATED CARBON TREATED PETROLEUM REFINERY WASTEWATER

	Aerated lagoon				Aquaculture				Activated carbon			
	B_1		B_2		C_1		C_2		D_1		D_2	
Date	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus	Dis	Sus
Sep 18 78	.06	.05	.05	.05	.05	.05	.05	.06	.06	.05	.10	.06
Sep 26 78	.05	.05	.06	.05	.39	.22	.10	.10	.05	.05	.05	.05
Oct 4 78	.17	.05	.17	.05	.11	.17	.11	.14	.14	.05	.14	.11
Oct 12 78	.21	.05	.21	.05	.11	.11	.11	.05	.14	.05	.14	.05
Oct 20 78	.33	.05	.30	.05	.11	.11	.05	.11	.24	.11	.24	.05
$\bar{x}$	.15	0	.15	0	.14	.12	.06	.08	.12	.02	.12	.03
SD	.13	0	.12	0	.15	.08	.06	.05	.09	.05	.09	.05

APPENDIX C

SPECIES LIST OF BENTHIC MACROINVERTEBRATES FROM
ON-SITE EVALUATION OF
DUAL MEDIA-ACTIVATED CARBON AND
AQUACULTURE TREATMENT SYSTEMS FOR
REMOVAL OF TOXIC CONSTITUENTS FROM PETROLEUM REFINERY WASTEWATER

TABLE C-1. SPECIES COMPOSITION OF BENTHIC MACROINVERTEBRATES EXPOSED TO NORMAL LAGOON TREATED OIL REFINERY WASTEWATER

	Days of exposure			
Species list	Start	8	16	32
Coelenterata				
Hydra sp.	1	-	-	-
Turbellaria				
Unidentified sp.	4	-	-	-
Annelida				
Hirudinea				
Unidentified sp.	1	-	-	-
Oligochaeta				
Dero sp.	633	385	351	100
Dero digitata Brinkhurst	118	104	159	44
Stylaria lacustris Brinkhurst	2	-	-	-
Pristina sp.	25	38	3	-
Aulophorus sp.	-	-	4	-
Arthropoda				
Hyalella azteca (Saussure)	42	8	-	-
Insecta				
Megaloptera				
Sialis sp.	1	-	-	-
Ephemeroptera				
Stenonema sp.	1	-	-	-
Odonata				
Argia sp.	264	202	145	132
Epicordulia sp.	2	-	-	-
Didymops sp.	1	-	-	-
Tetragoneuria sp. #1	1	3	2	2
Tetragoneuria sp. #2	1	3	1	-

Table C-1 (continued)

Species list	Days of exposure: Start	8	16	32
Coleoptera				
Dubiraphia sp.	18	5	1	-
Berosus sp.	43	38	36	31
Dineutus sp.	1	-	-	-
Tropisternus lateralis (Fabricius)	-	-	2	-
Trichoptera				
Orthotrichia sp.	1	-	-	-
Oxyethira sp.	3	-	-	-
Polycentropodidae # 1	7	8	3	1
Polycentropodidae # 2	7	2	1	-
Diptera				
Palpomyia #2	-	2	5	18
Palpomyia #4	3	7	7	1
Ephydra sp.	-	-	-	15
Chironomidae				
Stenochironomus sp.	1	5	1	-
Glyptotendipes sp.	283	365	467	346
Tribelos sp.	46	84	99	136
Ablabesmyia janta Beck	25	51	48	56
Cricotopus sp.	28	68	2	-
Labrundinia sp.	2	5	1	-
Dicrotendipes nervosus Mason	26	38	44	54
Procladius sp.	6	-	1	-
Tanypus sp.	1	670	2649	1367
Dicrotendipes modestus Mason	76	107	25	-
Einfeldia sp.	100	190	174	146
Polypedilum sp.	2	2	1	-
Micropsectra sp.	40	42	5	-
Cryptotendipes sp.	3	5	-	-
Clinotanypus sp.	2	1	3	1
Pseudochironomus sp.	2	2	1	-
Parachironomus sp.	2	9	3	1
Cryptochironomus sp.	1	10	1	-
Larsia sp.	-	10	6	15
Psectrocladius sp.	-	4	-	-
Chironomus sp.	-	12	14	23
Goeldichironomus sp.	-	20	192	1511
Endochironomus sp.	-	1	-	-
Ablabesmyia mallochi (Walley)	-	-	1	-
Mollusca				
Physidae				
Unidentified sp.	69	54	17	2
Planorbidae				
Unidentified sp.	25	9	5	-

Table C-1 (continued)

Species list	Days of exposure			
	Start	8	16	32
Sphaeriidae				
Unidentified sp.	19	10	21	39
Ancylidae				
Ferrissia sp.	-	-	2	-
Number of Species	44	38	39	22

TABLE C-2. SPECIES COMPOSITION OF BENTHIC MACROINVERTEBRATES EXPOSED TO AQUACULTURE TREATED OIL REFINERY WASTEWATER

Species list	Days of exposure			
	Start	8	16	32
Coelenterata				
Hydra sp.	1	-	-	-
Turbellaria				
Unidentified sp.	4	-	-	-
Annelida				
Hirudinea				
Unidentified sp.	1	-	-	-
Oligochaeta				
Dero sp.	633	456	666	572
Dero digitata Brinkhurst	118	48	169	162
Stylaria lacustris Brinkhurst	2	-	-	-
Pristina sp.	25	11	15	136
Aulophorus sp.	-	-	1	-
Arthropoda				
Hyalella azteca (Saussure)	42	11	4	31
Insecta				
Megaloptera				
Sialis sp.	1	1	1	-
Ephemeroptera				
Stenonema sp.	1	-	-	-
Callibaetis sp.	-	-	-	1
Odonata				
Argia sp.	264	175	173	100
Epicordulia sp.	2	-	-	-
Didymops sp.	1	-	-	-
Tetragoneuria sp. #1	1	-	-	6
Tetragoneuria sp. #2	1	2	1	-
Unidentified sp. #1	-	-	1	1
Unidentified sp. #2	-	-	-	2
Coleoptera				
Dubiraphia sp.	18	9	5	4
Berosus sp.	43	32	36	38
Dineutus sp.	1	-	-	-
Tropisternus lateralis (Fabricius)	-	-	-	3
Copelatus sp.	-	-	-	1

Table C-2 (continued)

Species list	Days of exposure: Start	8	16	32
Trichoptera				
Orthotrichia sp.	1	-	-	-
Oxyethira sp.	3	4	-	-
Polycentropodidae #1	7	1	5	2
Polycentropodidae #2	7	9	9	21
Diptera				
Palpomyia #2	-	-	1	44
Palpomyia #4	3	4	-	1
Ephydra sp.	-	-	2	1
Chironomidae				
Stenochironomus sp.	1	9	7	1
Glyptotendipes sp.	283	267	524	286
Tribelos sp.	46	35	60	70
Ablabesmyia janta Beck	25	27	50	77
Cricotopus sp.	28	31	33	6
Labrundinia sp.	2	-	-	4
Dicrotendipes nervosus Mason	26	39	38	75
Procladius sp.	6	-	1	-
Tanypus sp.	1	108	988	628
Dicrotendipes modestus Mason	76	34	52	7
Einfeldia sp.	100	74	161	115
Polypedilum sp.	2	2	1	15
Micropsectra sp.	40	28	25	6
Cryptotendipes sp.	3	-	-	-
Clinotanypus sp.	2	1	1	-
Pseudochironomus sp.	2	4	3	-
Parachironomus sp.	2	12	1	-
Cryptochironomus sp.	1	2	1	2
Larsia sp.	-	1	4	5
Psectrocladius sp.	-	2	-	-
Chironomus sp.	-	8	130	129
Goeldichironomus sp.	-	42	1345	6055
Endochironomus sp.	-	-	-	2
Ablabesmyia mallochi (Walley)	-	-	-	-
Demichryptochironomus sp.	-	-	2	-
Tanypodinae #1	-	-	1	-
Mollusca				
Physidae				
Unidentified sp.	69	31	71	33
Planorbidae				
Unidentified sp.	25	2	10	4
Spaeriidae				
Unidentified sp.	19	47	29	28

Table C-2 (continued)

Species list	Day of exposure			
	Start	8	16	32
Ancylidae				
Ferrissia sp.	-	-	21	3
Number of species	44	35	40	39

TABLE C-3. SPECIES COMPOSITION OF BENTHIC MACROINVERTEBRATES EXPOSED TO DUAL MEDIA-ACTIVATED CARBON TREATED EFFLUENT

Species list	Days of exposure			
	Start	8	16	32
Coelenterata				
Hydra sp.	1	-	-	-
Turbellaria				
Unidentified sp.	4	2	-	-
Annelida				
Hirudinea				
Unidentified sp.	1	-	-	-
Oligochaeta				
Dero sp.	633	541	297	25
Dero digitata Brinkhurst	118	52	96	8
Stylaria lacustris Brinkhurst	2	-	-	-
Pristina sp.	25	8	7	-
Aulophorus sp.	-	-	-	-
Arthropoda				
Hyalella azteca (Saussure)	42	20	15	15
Insecta				
Megaloptera				
Sialis sp.	1	1	2	-
Ephemeroptera				
Stenonema sp.	1	1	-	-
Callibaetis sp.	1	1	-	-
Odonata				
Argia sp.	264	143	89	104
Epicordula sp.	2	-	-	-
Didymops sp.	1	-	-	-
Tetragoneuria sp. #1	1	3	3	4
Tetragoneuria sp. #2	1	2	3	2
Unidentified sp. #1	-	-	-	1
Unidentified sp. #2	-	-	1	-
Coleoptera				
Berosus sp.	43	34	23	23
Dubiraphia sp.	18	6	7	3
Dineutus sp.	1	-	-	-
Tropisternus lateralis (Fabricius)	-	5	13	5
Trichoptera				
Orthotrichia sp.	1	-	-	-
Oxyethira sp.	3	-	-	-
Polycentropodidae #1	7	10	9	3
Polycentropodidae #2	7	4	6	11
Alisotrichia sp.	-	-	-	1

Table C-3 (continued)

Species list	Days of exposure			
	Start	8	16	32
Arthropoda				
Diptera				
Palpomyia #2	-	6	15	47
Palpomyia #4	3	2	4	2
Ephydra sp.	-	-	-	16
Chironomidae				
Stenochironomus sp.	1	12	15	5
Glyptotendipes sp.	283	669	766	861
Tribelos sp.	46	104	76	135
Ablabesmyia janta (Beck)	25	56	42	110
Cricotopus sp.	28	73	1	3
Labrundinia sp.	2	2	4	-
Dicrotendipes nervosus Mason	26	47	77	91
Procladius sp.	6	2	1	-
Tanypus sp.	1	816	1259	359
Dicrotendipes modestus Mason	76	151	80	3
Einfeldia sp.	100	223	313	176
Polypedilum sp.	2	2	1	1
Micropsectra sp.	40	39	15	7
Cryptotendipes sp.	3	-	-	-
Clinotanypus sp.	2	1	2	-
Pseudochironomus sp.	2	1	2	3
Cryptochironomus sp.	1	12	1	-
Larsia sp.	-	4	9	16
Psectrocladius sp.	-	6	-	-
Chironomus sp.	-	75	48	856
Goeldichironomus sp.	-	47	1944	7639
Endochironomus sp.	-	2	-	-
Ablabesmyia mallochi (Walley)	-	-	2	-
Parachironomus sp.	2	34	7	2
Conchapelopia sp.	-	-	2	-
Mollusca				
Physidae				
Unidentified sp.	69	49	26	33
Planorbidae				
Unidentified sp.	25	38	30	26
Sphaeriidae				
Unidentified sp.	19	21	66	73
Ancylidae				
Ferrissia sp.	-	31	-	13
Number of species	44	44	41	36